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State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009

État des ressources physiques et biologiques et de certaines ressources halieutiques des écosystèmes des eaux canadiennes du Pacifique en 2009

W.R. Crawford[1] and J.R. Irvine[2], editors
Fisheries Oceanography Working Group (FOWG)
Science Branch
Fisheries and Oceans Canada
Pacific Region

[1]Institute of Ocean Sciences, Sidney, BC V8L 4B2

[2]Pacific Biological Station, Nanaimo, BC V9T 6N7

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ABSTRACT

Monitoring the physical and biological oceanographic conditions and fishery resources of the Pacific Region is done semi-regularly by a number of government departments, to understand the natural variability of these ecosystems and how they respond to both natural and anthropogenic stresses. This eleventh report of an annual series updates the state of physical, biological, and selected fishery resources of Canadian Pacific marine ecosystems.

One of the biggest stories for 2009 was the return of far fewer Sockeye salmon than expected. Accurately forecasting salmon returns is difficult as there are few observations of salmon between the time adults spawn in fresh water, and the time the next generation returns to British Columbia waters. Scientists base predictions of numbers of returning adult Sockeye salmon primarily on the empirical relationship between stock size (spawners, returns, or smolts depending on the stock) and consequent recruitment. For 2009, the forecast indicated there was a 90% probability the total run would be between 3.5 and 37.6 million Sockeye, yet the actual number was less than 2 million. Efforts to incorporate ocean indices to improve forecast performance were examined, and show promise for certain stocks; however, not Fraser River sockeye salmon at this time.

Ocean temperatures off the west coast on Canada were cooler than normal at the beginning of 2009 but warmed through the summer and autumn. By early 2010 most regions along the American and Canadian west coast were above normal in temperature. The shift from cool to warm is likely in response to a change from La Niña to El Niño conditions in the tropical Pacific and a shift in ocean temperature patterns all across the North Pacific Ocean, called the Pacific Decadal Oscillation. The North Pacific Current has declined in strength from its peak flow in 2008. This eastward current splits into a northward flowing Alaska Current and southward flowing California Current, when it approaches the west coast of North America. The Alaska Current flow, in 2009, was the strongest in the eight years of continuous observations provided by the International Argo Program.

Zooplankton are small animals drifting in the ocean's currents. The type of zooplankton available is thought to determine the growth and survival rates of juveniles of many endemic marine species. Species off the coast of Oregon and British Columbia, in the spring of 2009, were dominated by cool water groups that might be a better food source for endemic (native) marine life. These cool-water zooplankton dominated for the past three years of cooler ocean temperatures, although the dominant groups shifted to warm-water species in late summer 2009, along the outer continental shelf of southern Vancouver Island. Perhaps in response to the dominance of cool-water zooplankton in spring and early summer, many endemic species of seabirds on Triangle Island and in Pacific Rim Nature Preserve successfully raised chicks. Pink (smooth) shrimp numbers off the west coast of Vancouver Island increased in the May surveys of 2008 and 2009, from very low levels during 2004-2007. Such increases appear related to colder water when the shrimp were young, and to low abundances of Pacific hake. Many juvenile salmon from the Columbia River and west coast of Vancouver Island were larger in size or more numerous, or both, through spring and early summer of 2009, but their growth rates through summer and early autumn were low. Biomass of adult herring off Vancouver Island were low, attributed to several factors, including warmer ocean temperatures prior to 2007,

when these adults were young and most sensitive to ocean temperatures and to the predators and prey associated with these conditions. Catches of Albacore tuna in Canadian waters, in 2009, were lower than average, attributed to these cooler ocean temperatures. As noted above, several species along the west coast of Vancouver Island appear sensitive to interannual changes in ocean temperature; elsewhere this link is not as clear, and the timing of spring conditions or presence of predators might be more relevant. For example, herring in the Strait of Georgia are relatively high in number and year-to-year changes in their biomass does not follow changes in temperature.

Humboldt squid appeared off the west coast in record high numbers in 2009. They were most abundant at several hundred metres depth, just seaward of the continental shelf among schools of Pacific hake, and were likely feeding on hake. Many of these squid were also observed closer to shore, and scores were found dead on west coast beaches. The biomass of Pacific hake off the Canadian coast seemed low, but assessment was difficult due to the many squid also observed among them.

Several highlights are specific to the waters of central and northern British Columbia, which form the Pacific North Coast Integrated Management Area (PNCIMA). This region warmed later in the year than the Oregon, Washington and southern British Columbia coasts. Zooplankton species here also continued the dominance of cool-water groups. There are three stocks of herring in PNCIMA, and the biomass of adults of all three stocks is relatively low. Their biomass might increase if hake numbers remain low. The abundance of central and north coast Chinook salmon seems to be rebounding, from a low in 2008.

Surface temperatures were generally above normal at most lighthouse stations in 2009 in the Strait of Georgia and Juan de Fuca Strait, but below the surface the waters remained relatively cool. Very high concentrations of phytoplankton were observed during the ship-based survey in April in the Strait of Georgia and in summer in Juan de Fuca Strait. Both were dominated by diatoms, as is normal for these regions. Satellite observations provide estimates of the concentration of phytoplankton at the ocean surface, when ship-based sampling is unavailable. These satellite observations reveal that when a plankton bloom appears very early in the Strait of Georgia, it is often associated with a bloom that is found in Malaspina Strait and also in Jervis Inlet. When viewed from space this bloom sometimes takes on the shape of a dragon, and it has acquired the name "Malaspina Dragon." These satellite measurements became available in 2001, and the Dragon appeared in 2005, 2008, and 2009.

Finally, measurements of contaminants in cores from the bottom of the Strait of Georgia reveal past changes in the relative concentrations of contaminants in this region. Most contaminants that have been banned for many years, such as lead in gasoline and PCBs, are declining in concentration. In contrast, the concentration of flame retardant polybrominated diphenyl ethers (PBDEs) is increasing rapidly in sediment, despite its recent ban in Canada.

RÉSUMÉ

La surveillance des conditions physiques et biologiques de l'océan ainsi que des ressources halieutiques de cette région est effectuée de façon semi-régulière par certains ministères afin que nous puissions comprendre la variabilité naturelle de ces écosystèmes et leur réaction aux facteurs de perturbation d'origine naturelle et anthropique. Le présent rapport est le onzième d'une série annuelle décrivant l'état des ressources physiques, biologiques et de certaines ressources halieutiques des écosystèmes des eaux canadiennes du Pacifique.

Un des événements marquants de 2009 fut un taux de retour du saumon rouge beaucoup plus faible que prévu. Il s'avère difficile de prévoir avec exactitude les remontes du saumon car il existe peu de données sur le saumon entre la période de frai des adultes en eau douce et celle du retour de la génération suivante dans les eaux de la Colombie-Britannique. Les prévisions scientifiques des remontes du saumon rouge se fondent principalement sur la relation empirique entre l'effectif du stock (géniteurs, remontes ou saumoneaux, selon le stock) et le recrutement subséquent. Pour 2009, on prédit, avec une probabilité de 90%, que la remonte totale de saumon rouge serait entre 3.5 et 37.6 millions. Cependant, la remonte actuelle totalisa moins de 2 millions. On a examiné les efforts visant à améliorer les prévisions par l'inclusion d'indices océaniques, ce qui semble prometteur pour certains stocks, cependant pas pour le saumon rouge du fleuve Fraser en ce moment.

La température de l'océan au large de la côte ouest du Canada était plus fraîche que la normale au début de 2009 mais s'est réchauffée durant l'été et l'automne. Au début 2010, la température de la plupart des régions le long de la côte ouest canadienne et américaine était supérieure à la normale. Ce réchauffement fut probablement provoqué par un changement des conditions La Niña à celles de El Niño dans le Pacifique tropique et par un changement de la température océanique dans l'ensemble de l'océan Pacifique nord, connu sous le nom d'oscillation décennale du Pacifique. La force du courant du Pacifique nord a diminué depuis son maximum en 2008. Ce courant vers l'est se divise en deux branches à l'approche de la côte ouest de l'Amérique du Nord: le courant de l'Alaska qui coule vers le nord et le courant de Californie qui se dirige vers le sud. La force du courant de l'Alaska en 2009 était la plus forte jamais observée pendant les huit ans d'observation continuelle provenant du programme international Argo.

Les zooplanctons sont de petits animaux portés par les courants marins. On pense que le type de zooplancton disponible détermine la croissance et le taux de survie des juvéniles de plusieurs espèces marines endémiques. Au printemps de 2009, les espèces au large de la côte de l'Orégon et de la Colombie-Britannique comprenaient surtout des espèces d'eaux fraîches qui pourraient être une meilleure source de nourriture pour la vie marine endémique (indigène). Ces zooplanctons d'eau fraîche prédominèrent durant ces trois dernières années de température océanique plus fraîche. Cependant, à la fin de l'été 2009, les espèces d'eau chaude sont devenues les plus nombreuses le long de la partie extérieure du plateau continental du sud de l'île de Vancouver. Il se peut que cette dominance du zooplancton d'eau fraîche contribuât au succès de la reproduction de plusieurs espèces endémiques d'oiseaux marins à l'île Triangle et dans la réserve naturelle Pacific Rim. Les relevés de mai 2008 et 2009 ont révélé une augmentation du nombre de crevettes roses (lisses) au large de la côte ouest de l'île de Vancouver, par rapport aux très faibles abondances entre 2004 et 2007. Il semble que ces augmentations correspondent à la présence d'eau relativement froide lorsque les crevettes étaient jeunes ainsi qu'à la faible abondance du merlu du Pacifique. Bon nombre de saumons juvéniles issus du fleuve Colombia et de la côte ouest de l'île de Vancouver était de plus grande taille ou plus nombreux, ou les deux, au printemps et au début de l'été 2009, mais leur taux de croissance pendant l'été et le début de l'automne fut faible. La faible biomasse du hareng adulte

au large de l'île de Vancouver peut être attribué à plusieurs facteurs, y inclus les températures chaudes océaniques précédant 2007 lorsque ces adultes étaient jeunes et plus sensibles aux températures océaniques et aux prédateurs et proies associés à ces conditions. Il semble que les températures océaniques plus basses ont entraîné des prises de thon blanc inférieures à la normale dans les eaux canadiennes en 2009. Tel qu'indiqué ci-dessus, plusieurs espèces le long de la côte ouest de l'île de Vancouver semblent être sensibles aux changements interannuels de température océanique; ce lien n'est toutefois pas aussi évident ailleurs où l'arrivée des conditions printanières ou la présence de prédateurs pourrait être plus pertinent. Par exemple, le hareng du détroit de Géorgie est relativement abondant et les variations annuelles de sa biomasse ne suivent pas les changements de température.

En 2009, un nombre record de calmars de Humboldt est apparu au large de la côte ouest. Ils abondaient à une profondeur de quelques centaines de mètres, au large de plateau continental, parmi les bancs de merlu du Pacifique, et il est probable qu'ils s'alimentaient de merlu. Plusieurs de ces calmars furent aussi observés plus près de la rive et on en a trouvé plusieurs morts sur les plages de la côte ouest. La biomasse du merlu du Pacifique au large de la côte canadienne semblait basse, mais le nombre de calmars parmi eux a rendu l'évaluation difficile.

Plusieurs points saillants portent sur les eaux de la partie centrale et nord de la Colombie-Britannique qui forme la Zone de gestion intégrée de la côte nord du Pacifique (ZGICNP). Cette région s'est réchauffée plus tard dans l'année que les côtes de l'Orégon, Washington et du sud de la Colombie-Britannique. Les espèces de zooplancton retrouvées ici étaient également composées en majeure partie d'espèces d'eau froide. Il existe trois stocks de hareng dans la ZGICNP et la biomasse des trois stocks est plutôt faible. Leur biomasse pourrait augmenter si l'abondance du merlu reste faible. Le taux d'abondance du saumon quinnat de la côte centrale et nord semble remonter après le faible taux de 2008.

La température de surface est restée généralement au dessus de la normale aux stations de phares dans le détroit de Géorgie et de Juan de Fuca en 2009, mais les eaux sous la surface sont demeuré plutôt fraîches. De fortes concentrations de phytoplancton ont été observées durant le relevé effectué à bord d'un navire en avril dans le détroit de Géorgie et en été dans le détroit de Juan de Fuca. Ces concentrations consistaient surtout de diatomées, la norme pour ces régions. Les observations satellite fournissent une estimation de la concentration de phytoplancton à la surface de l'océan même lorsque l'échantillonnage à bord de navire n'est pas disponible. Ces observations satellitaires révèlent que l'arrivée précoce d'une prolifération phytoplanctonique dans le détroit de Géorgie est souvent associée à une prolifération dans le détroit de Malaspina et aussi dans le bras de mer Jervis. Cette prolifération prend parfois la forme d'un dragon lorsqu'on l'observe à partir de l'espace, et a donc acquis le nom de « Dragon de Malaspina ». Ces mesures satellitaires sont devenues disponibles en 2001 et le dragon est apparu en 2005, 2008 et 2009.

En dernier lieu, la mesure des contaminants dans les carottes extraites du fond du détroit de Géorgie indique des changements antérieurs de la concentration relative des contaminants dans cette région. La concentration de la plupart des contaminants qui ont été bannis depuis plusieurs années, tel que le plomb dans l'essence et les BPCs, diminue. En revanche, la concentration des éthers diphényliques polybromés EDP provenant de produits ignifuges augmente rapidement dans les sédiments malgré son interdiction récente au Canada.

INTRODUCTION

This report is the eleventh in an annual series updating the state of physical, biological, and selected fishery resources of Canadian Pacific marine ecosystems. Canadian Pacific marine waters lie in a transition zone between coastal upwelling (California Current) and downwelling (Alaskan Coastal Current) regions, and experience strong seasonality and considerable freshwater influence. Variability is closely coupled with events and conditions throughout the tropical and North Pacific Ocean, experiencing frequent El Niño and La Niña events particularly over the past decade. The region supports important resident and migratory populations of invertebrates, groundfish and pelagic fishes, marine mammals and seabirds. Monitoring the physical and biological oceanographic conditions and fishery resources of the Pacific Region is done semi-regularly by scientific staff in several government departments, to understand the natural variability of these ecosystems and how they respond to both natural and anthropogenic stresses. Support for these programs is provided by Fisheries and Oceans Canada, Environment Canada, and various other agencies.

This year's Fisheries Oceanography Working Group (FOWG) meeting at the Pacific Biological Station in Nanaimo, BC was preceded by a one day salmon workshop on 16 February 2010. This special workshop, chaired by Jim Irvine, examined ways to better incorporate oceanographic and climatic information into predictions of salmon survival and abundance; A total of 13 presentations were made, highlights of which were presented at the larger FOWG meeting and are included in this report.. At the FOWG meeting on 17-18 February about 50 scientists met for presentations on the state of the ocean and its marine life in 2009 and early 2010.The FOWG meeting was chaired by Jim Irvine and Bill Crawford, both of Fisheries and Oceans Canada. Bill and Jim subsequently produced this report based on contributions by participants.

Assessment highlights in the format of top stories from this year's FOWG meeting are provided on the next pages. The agenda for this meeting is in Appendix 1. The list of participants is in Appendix 2 and detailed contributions by participants are found in Appendix 3. The contributions in Appendix 3 have not been formally peer-reviewed.

This report and others dating back to 1999 can be found at:

English: http://www.pac.dfo-mpo.gc.ca/science/psarc-ceesp/osrs/index-eng.htm

French: http://www.pac.dfo-mpo.gc.ca/science/psarc-ceesp/osrs/index-fra.htm

ASSESSMENT HIGHLIGHTS

LOW RETURNS OF SOCKEYE SALMON TO THE FRASER RIVER

Far fewer Sockeye salmon returned to the Fraser River in 2009 than expected. Scientists base predictions of numbers of returning adult Sockeye primarily on the time series of estimates of survivals between young and adult salmon. Accurately forecasting adult salmon returns is challenging, as there are many factors that affect the survival of fry that rear in freshwater systems, juvenile salmon that live in the ocean, and adult salmon as they return to spawning locations in freshwater. For 2009, the forecast of Fraser River Sockeye indicated there was a 90% probability the total run would be between 3.5 and 37.6 million Sockeye, yet the actual number was less than 2 million.

In 2009, returns were below the forecasted 10% probability level (Figure 1). In generating the 2009 forecast, long-term average productivities had been assumed, which seemed reasonable given that marine indicators suggested that conditions for salmon going to sea in 2007 would be relatively good. Separate work is ongoing to examine the utility of other indicators, concentrating on those in the early marine environment of young Fraser Sockeye, in an attempt to help to reduce the uncertainties in forecast methodology.

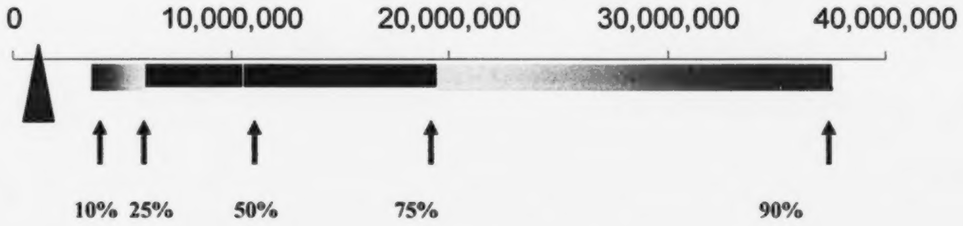


Figure 1. The 2009 total forecast probability distributions (indicated by blue arrows) for all Fraser Sockeye salmon stocks and 2009 preliminary returns (red triangle). Black horizontal bars represent the 25% to 75% probability distribution range with the 50% probability level indicated by the white vertical line and the blue (lighter) horizontal bars represent the 10% to 90% probability distribution range. (Contributed by Sue Grant of DFO and Catherine Michielsens of Pacific Salmon Commission)

Most Fraser River Sockeye enter the ocean in their second year of life and return as adults in their fourth year. For the 2009 adult return of Fraser River sockeye (2005 brood year, 2007 ocean entry), the productivity (recruits-per-effective female spawners) was amongst the lowest on record for most stocks. Sockeye salmon originating from the Harrison Lake have a different life history strategy from most other Fraser River stocks in that they enter the ocean in their first year of life and return as adults in their third fourth year. The 2009 return of adult Harrison Lake Sockeye, comprised of predominantly three year old fish from the 2006 brood year, exhibited below average productivity (preliminary estimate). It is of interest to note that Harrison Lake Sockeye productivity (2005 brood year, adults returned in 2008 and 2009) was the lowest on record, similar to other Fraser River Sockeye from the same brood year.

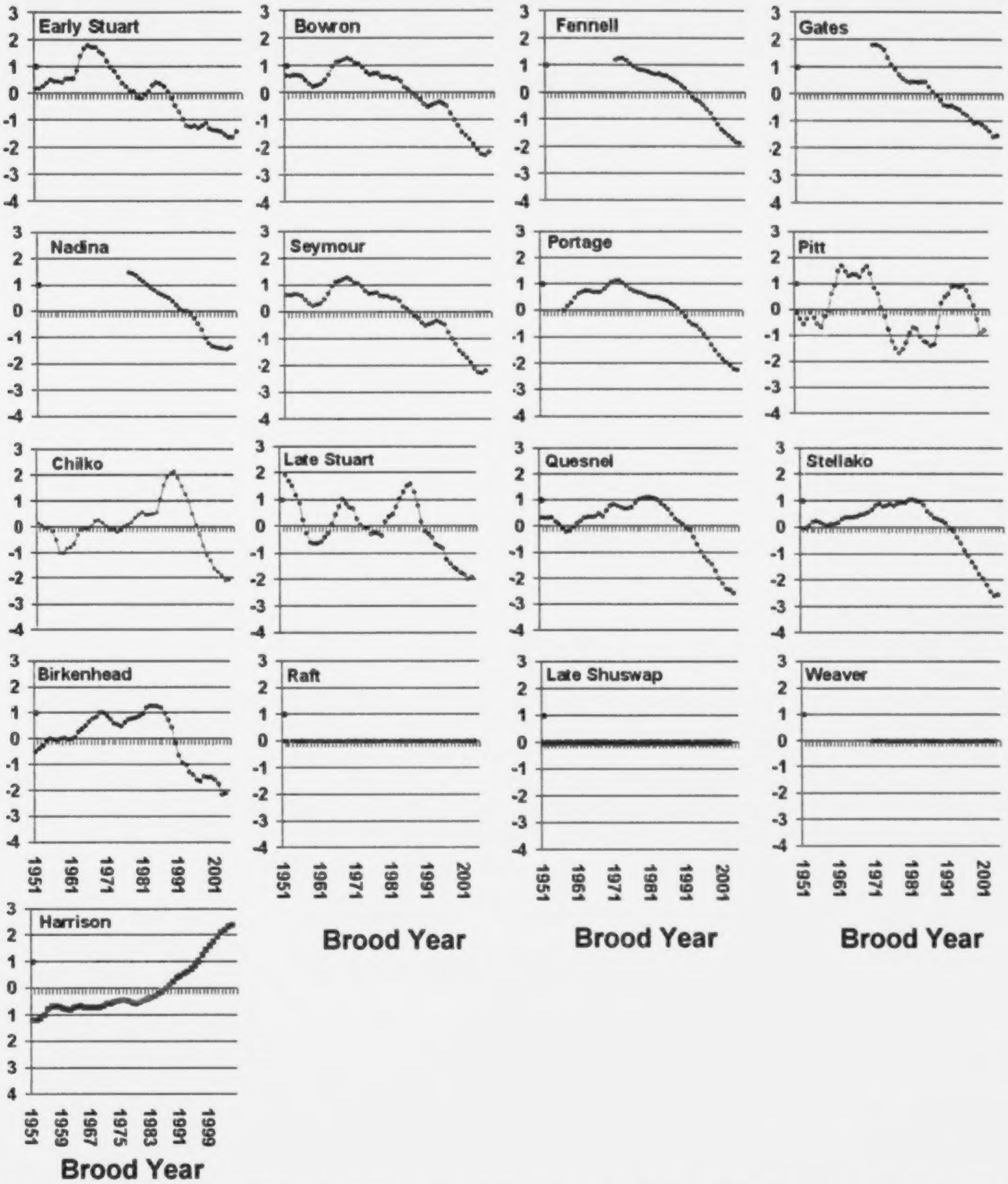


Figure 2. Time series of productivity (Kalman filtered annual Ricker [stock-recruitment] model 'a parameter values) estimates for each of 17 stocks (Cultus and Scotch excluded), scaled to a mean of zero and a standard deviation of one for stocks with long term productivity declines (red circles), stocks without declines (green diamonds), and the Harrison stock that has increased (light blue squares). The Kalman filter approach describes systematic long-term trends in productivity rather than short term variability in productivity (Dorner et al. 2008). Base code from Dorner et al. 2008. (Contributed by Sue Grant of DFO and Catherine Michielsens of Pacific Salmon Commission)

The 2006 brood year productivity for Harrison Sockeye, with the same ocean entry year (2007) as most other Fraser Sockeye that returned in 2009, were below average but improved relative to the 2005 brood year. Harrison Sockeye salmon have an unusual age structure and life history. They are age-3 (3_1) and 4 (4_1), migrating to sea shortly after emergence. Most Fraser Sockeye age-4 (4_2) and 5 (5_2) fish spend a full year rearing in lakes prior to ocean migration.

Fraser Sockeye salmon productivities were estimated with Kalman filtered (KF) Ricker *a* parameters, which describe long term systematic trends in $\log_e$(recruits-per-spawner) (Dorner et al. 2008). Since the 1960's, KF Ricker *a* annual parameter values decreased for 13 of 17 stocks (Cultus and Scotch were not included in this assessment) (Figure 2). Three stocks, including Raft, Late Shuswap and Weaver have not exhibited systematic productivity trends (Figure 2). For these three stocks, all variability in $\log_e$(recruits-per-spawner) was attributed by the KF Ricker model a parameter values to short-term variability (noise) rather than long-term systematic trends (signal) (Dorner et al. 2008). Late Shuswap is expected to dominate returns in 2010. Harrison Sockeye have increased in productivity (Figure 2).

YEAR OF THE HUMBOLDT SQUID

In 2009, Humboldt squid were much more widespread and abundant in British Columbia waters than in previous years. They were recorded in both commercial and research catches from early July to October (Figure 3). They were densely aggregated; a three minute research tow yielded nearly 120 individuals and commercial bycatches were occasionally estimated in the tens of tons. In addition to catches and numerous sightings there were 10 significant stranding events reported throughout the exposed coast (Ucluelet to Massett) between August and October, as well as individuals washed onshore in Campbell River and Puget Sound in December.

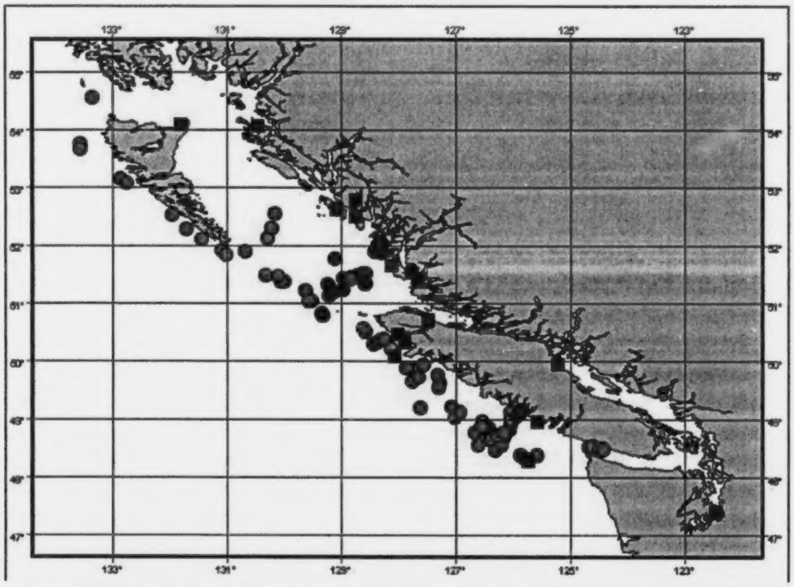
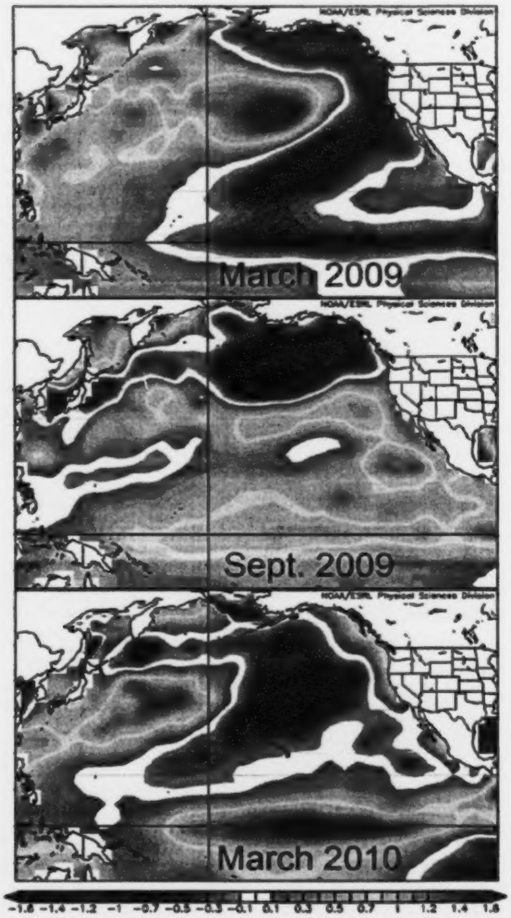


Figure 3. Records of Humboldt squid, Dosidicus gigas, *from British Columbia and Puget Sound in 2009 (blue squares are sightings, red squares are strandings, red circles are commercial bycatch and green circles are research catches). (Contributed by Graham Gillespie, DFO)*

Humboldt squid are seasonally-migrant, high-metabolism predators that can function as keystone predators in offshore and nearshore ecosystems. Most arrived in BC waters in summer 2009, and departed in autumn for southern US waters. They prey primarily on pelagic species such as hake, myctophids, anchovies, sardines, pelagic rockfish and other squid. Their diet could shift in northern waters depending on prey abundance, in particular depending upon the degree of overlap in time and space with salmon and herring.

Humboldt squid were observed frequently in the 2009 USA/Canada survey of Pacific hake along the west coast of Canada to central California. Both species tend to stay at depths of a few hundred metres, just seaward of the continental shelf during the day. There were so many squid among these hake that the normal acoustic images used to estimate hake abundance were highly irregular and not useable for the hake assessment itself. Humbolt squid are known to feed on Pacific hake. Their impact on hake numbers (and perhaps other marine species in summer) in future years could be extensive.

WEST COAST WATERS ARE WARMING AFTER SEVERAL COOL YEARS


NOAA/ESRL Physical Sciences Division
March 2009
NOAA/ESRL Physical Sciences Division
Sept. 2009
NOAA/ESRL Physical Sciences Division
March 2010
-1.6 -1.4 -1.2 -1 -0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7 1 1.2 1.4 1.6

In last year's report the lead story described the unusually cold ocean waters west of British Columbia, Oregon and Washington all through 2008. These cold waters were still present in March 2009, as shown by the purple regions in the top panel of Figure 4 at left. In this plot the purple shading indicates more than a Celsius degree colder temperature than normal. In many areas it was much colder.

By August and September of 2009 the cold waters were farther offshore, with slightly warmer than normal temperature off Vancouver Island and all waters south to Mexico. These features are in the middle panel at left.

By March 2010 the waters near Canada and USA were warmer than normal, from shore out to several hundred kilometres, as shown by the yellow shading in the bottom panel at left. The cold waters were pushed farther south.

Figure 4. Ocean temperature anomalies in the Pacific Ocean. The map extends from North America to Asia, and from 65°N to 15°S. The Equator is marked by a horizontal black line in each panel; The vertical black line marks 180°W. The anomaly scale (at bottom) extends from minus 1.6°C in purple to plus 1.6°C in dark red. Images provided by NOAA Earth System Research Laboratory. (Contributed by Bill Crawford, DFO.)

This shift from cold to warm water west of Canada and the USA (including Alaska) accompanied a shift from La Niña to El Niño conditions on the Pacific Equator, which took place in 2009. In Figure 4 above one can see this shift in the change of colour along the Pacific Ocean Equator (horizontal black line in each panel), from purple in March 2009 to yellow-orange in September 2009, and finally to solid red in March 2010. This region on the Equator is "El Niño Central", where ocean temperatures respond most strongly to changes in the Southern Oscillation. The official El Niño and La Niña indices are defined by ocean temperature anomalies there. From mid-2009 to at least April 2010 these waters were sufficiently warm to trigger an official "El Niño" event, the strongest of this century.

In general, ocean temperatures along the Canadian and American west coast are *relatively* warm in El Niño winters and cool in La Niña winters. (The *relative* measure indicates warm and cool compared to normal temperatures for that month.) By this standard the shift to warm waters in 2010 was expected, and also predicted. (Air temperatures are normally warm too, and the warming in January to February 2010 impacted the Vancouver Olympic Games.)

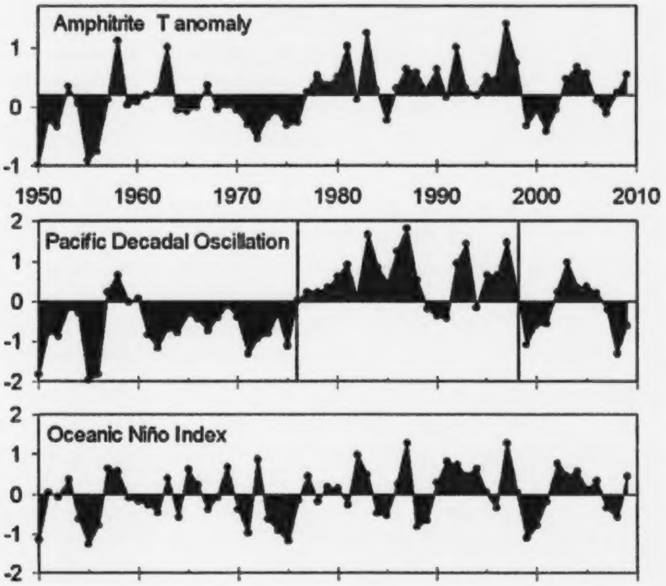


Figure 5. Anomalies of annual ocean temperature at Amphitrite Point, compared to time series of the Pacific Decadal Oscillation and the Oceanic Niño Index. (Contributed by Bill Crawford of DFO)

We can compare changes in local ocean temperatures with El Niño in Figure 5 at left. Amphitrite Point is a station on the southwest coast of Vancouver Island where ocean temperature has been measured daily since the 1930s.

The annual temperature anomaly here is compared in Figure 5 to annual values of the Pacific Decadal Oscillation (PDO) and the Oceanic Niño Index (ONI). PDO represents a pattern of temperature anomalies in the North Pacific Ocean, whereas ONI measures temperature anomalies in "El Niño Central" on the Equator of the Pacific Ocean. Generally an El Niño or La Niña triggers changes in atmospheric weather patterns in the North Pacific, which in turn can impact both PDO and Amphitrite temperatures. However, the PDO is also sensitive to slow changes in ocean currents in the western North Pacific Ocean. Until 1976, Figure 5 it was mostly negative (a gray line marks this shift in 1976), but after 1976 and up to 1998 it was mostly positive (a second gray line marks 1998).

It has become common in the past ten years, since the discovery of the PDO by Nate Mantua, Steven Hare and colleagues, to attribute changes in ocean temperature and marine life along the west coast to PDO, based on the co-variability of PDO and local ocean temperatures until the 1990s. For example, one can see in Figure 5 that Amphitrite and PDO track each other well. However, since 1998 both the PDO and ONI have varied in phase, with common positive and negative intervals. As a result, ONI itself has become a useful indicator of local ocean temperatures, and because it tends to shift in phase before the PDO, it is a more useful predictor. We do not know if such co-variability of PDO and ONI will continue, but for now we can predict changes in local temperature and marine life reasonably well with the Oceanic Niño Index. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

SMALL MARINE LIFE IN TRANSITION AS WEST COAST WATERS WARM

Scientists of Fisheries and Oceans Canada estimate abundance and biomass for more than 50 zooplankton species, collected primarily during spring and late summer research cruises along the west coast of Vancouver Island and other locations. Zooplankton are small, often microscopic animals that drift in the ocean's currents. In the 30 years of these measurements, an alternating cold-warm pattern of species has emerged, with different species of zooplankton dominating in cold ocean years than in warm years. They are a sentinel of shifts in marine life, since they are usually the first species observed to respond to changes in ocean temperature. It appears that cold-water zooplankton species provide a richer source of food for predators than similar warm-water species.

In 2009 there was an almost complete shift in zooplankton species on the outer continental shelf of the west coast of Vancouver Island between late May and early September. The spring community was very strongly dominated by cool water crustaceans such as large copepods and euphausiids. The late summer and autumn communities were dominated by two warmer water non-crustacean taxa: the pteropod *Clio pyramidata*, and the doliolid *Dolioletta gegenbauri*. Southern copepods also increased from May to September, despite the fact that their usual annual maximum is during winter when southerly winds drive peak poleward transport from southern source regions. *Clio* and *Dolioletta* are both individually large (circa 1 cm body length), but are probably too large and also too gelatinous and lipid-poor to be optimal prey for summer predators such as juvenile salmon, herring, and planktivorous seabirds.

Over the past 30-50 years, both *Clio* and *Dolioletta* were historically occasional biomass dominants off southern California. They were observed very rarely and intermittently off British Columbia. However, this latitudinal gradient of occurrence and dominance has changed dramatically this century. Figure 6 shows time series of annual anomalies of *Clio* and *Dolioletta* over the southern Vancouver Island continental shelf break and slope. Both species were either absent, or present only at very low abundance/biomass prior to 2000. Since the turn of the century, doliolids have had strong positive anomalies in most years. Generally, the abundance of copepods decreases as the abundance of *Dolioletta* increases in a given area. *Clio* is now occasionally extremely abundant. All 3 years with large positive anomalies of *Clio* have been during the past decade.

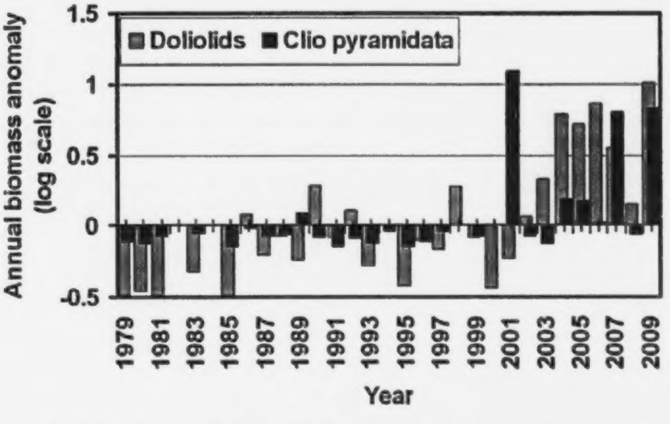


Fig. 6. Anomaly time series for large gelatinous herbivorous zooplankton off southern Vancouver Island. Graphed are doliolids (mostly Dolioletta gegenbauri*) and warm water thecosomatous pteropods (*Clio pyramidata*). Both are endemic to the mid-latitude Pacific south of the subtropic-subarctic transition zone, but occasionally invade the eastern subarctic Pacific. The frequency and intensity of invasion has increased dramatically since about 2000. (Contributed by David Mackas of DFO.)*

Bill Peterson of the NOAA Northwest Fisheries Sciences Center samples the ocean every two weeks off Newport Oregon, providing the most highly resolved time series of fast changes in zooplankton. He has observed how Pacific-wide changes in weather lead to shifts in ocean temperature near Newport, and also to changes in zooplankton. As a measure of the zooplankton community, he uses the copepod species richness, which is the number of copepod species observed in biweekly plankton samples. In general, warm waters have more species and this holds true for his Oregon time series.

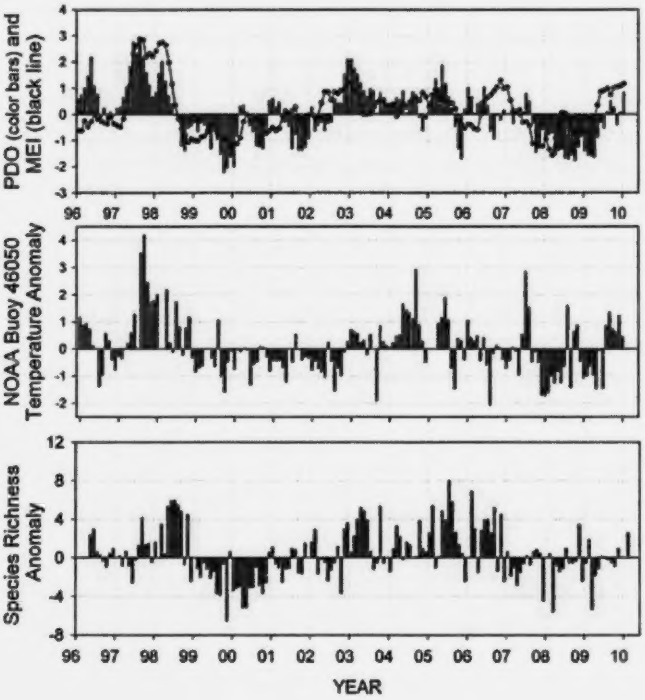


Figure 7. ***Upper Panel****. Time series of the Pacific Decadal Oscillation (PDO) and Multivariate ENSO Index (MEI) from 1996-2010.* ***Middle Panel****. Time series of monthly average sea surface temperature anomalies measured at the NOAA Buoy 46050 located 17 miles off Newport Oregon. Anomaly is calculated from the base period of 1991-2008.* ***Lower Panel****. Time series of the anomaly of monthly averaged species richness of copepods collected at a baseline station located 9 km off Newport. Species richness is the number of copepod species in a given zooplankton sample. Note that a persistent change in the sign of MEI is usually followed by change in sign of the PDO; note also that SST and copepod species richness follow MEI and PDO with a few months time. (Contributed by Bill Peterson of NOAA/Northwest Fisheries Science Center)*

Bill Peterson applies the MEI, which is a time series of El Niño and La Niña closely related to the Oceanic Niño Index shown previously. One can see in Figure 7 that MEI, PDO and copepod species richness generally follow similar patterns from month to month. Species richness is another indicator of seasonal and interannual variations in ocean conditions. (Species richness is simply the number of copepod species observed in biweekly plankton samples.) Monthly average values for copepod species richness continue to track quite closely with the PDO and SST (Figure 7) such that when the PDO is negative, the copepod community is dominated by only a few cold–water, subarctic species. Conversely, when the PDO is positive, SST on the Oregon shelf is warm, and the copepod community is dominated by a greater number of warm–water, subtropical species. During 2009, there was moderately low biodiversity, but certainly no indication of an influx of an anomalously high number of subtropical species. This suggests that the warming observed in 2009 was localized, and not due to any northward transport of subtropical waters during summer or autumn of 2009 as a result of the El Niño event. Northern copepod biomass anomalies, for the year 2009, were also fairly high, 0.45, similar to values seen in 2007 (0.50), but less than values in 2008 (0.75).

By early 2010, Oregon coastal waters were above normal temperature, likely due to changes in wind patterns associated with El Niño.

COOL WINTER AND SPRING IS GOOD NEWS FOR MANY ENDEMIC SPECIES OFF THE WEST COAST OF VANCOUVER ISLAND

Relatively cool ocean waters were observed off Vancouver Island all through winter and spring of 2009. These relatively cool waters arrived in 2007 and persisted until waters warmed in summer 2009.

The cool ocean temperatures during the first half of 2009 were good news for many endemic (i.e. native) marine species. Often it is the availability of suitable prey that determines how a species responds to changes in temperature. Since cool water zooplankton are generally more energy rich than warm water zooplankton, temperature related shifts in zooplankton species composition can influence the survival and growth of animals that consume zooplankton. Another factor is predator abundance, which can also be linked to ocean temperature.

A second measure of a cool-warm shift is the timing of spring transition off Vancouver Island. This transition marks the end of storm winds from the south and the onset of prevailing winds from the north. Since northerly winds are generally cool and also upwell cool waters along the coast, an early spring transition indicates cool ocean waters in spring. Scientists have tracked the timing of this transition for many years, monitoring the data from weather buoys and current meter moorings off Vancouver Island. Both data sets reveal earlier spring transition in 2009.

It appears an early spring transition is linked to years of good seabird breeding success. For example, when April ocean temperatures are cool and the spring transition is early, more juvenile auklets on Triangle Island survive to fly away from the nest. This island, off northern Vancouver Island, has the greatest concentration of seabirds in BC. Cool temperatures and northerly winds are indicators of the availability of good prey in nearby waters all through spring. Cassin's auklets on Triangle Island bred more successfully in 2007-2009, as expected for cool springs with early spring transition. In the Pacific Rim Marine Park Reserve off the west coast of Vancouver Island (WCVI), scientists note that most species of seabirds (except for the common murre) responded positively to the cooler local oceanic conditions observed in 2007 and 2008.

Recent surveys found the biomass of Pink shrimp (smooth) off WCVI, increased in 2008 and again in 2009, from very low levels during 2004-2007. Such increases appear related to colder water in previous years when the shrimp were young (this species has a 2-yr time lag from hatch to recruitment at age-2) and to low abundances of Pacific hake (a potential shrimp predator) in May surveys in 2008 and 2009.

Juvenile salmon usually survive their first year better along the outer Vancouver Island coast when spring and summer are cool. It is not ocean temperature itself that controls survival but, as noted above, it is likely the impact of temperature on their prey and/or predators.

Juvenile salmon along the outer Vancouver Island coast generally survived very well in the cool years of 2007 and 2008, and apparently in 2009 until waters warmed in summer. Catches of juvenile Chinook salmon (from the Columbia River) off the Washington and Oregon coast in June 2009 were the 4th highest in 12 years of sampling, attributed by American scientists to cool ocean waters. In Canadian waters, catch rates of juvenile Chum, Sockeye and Chinook salmon off Vancouver Island were highest ever in 2008. These are a mixture of Columbia and WCVI stocks.

Warmer water during the summer of 2009 may have negatively affected some juvenile Coho salmon. Their numbers in the spring 2009 survey were the highest ever, as noted in the left panel (final data point) of Figure 8 below. However, their growth rate between May and October 2009 was one of the lowest since observations began in 1998, coinciding with the onset of warmer local waters. We cannot determine conclusively why the growth rate plummeted, but their poor growth coincides in time with the shift of zooplankton species in these waters between May-June and August-September 2009, from cool-water species in May-June to warm-water species in August-September. (Details on this shift were described earlier.) However, zooplankton species shift was strongest on the outer continental shelf and juvenile Coho tend to stay closer to shore.

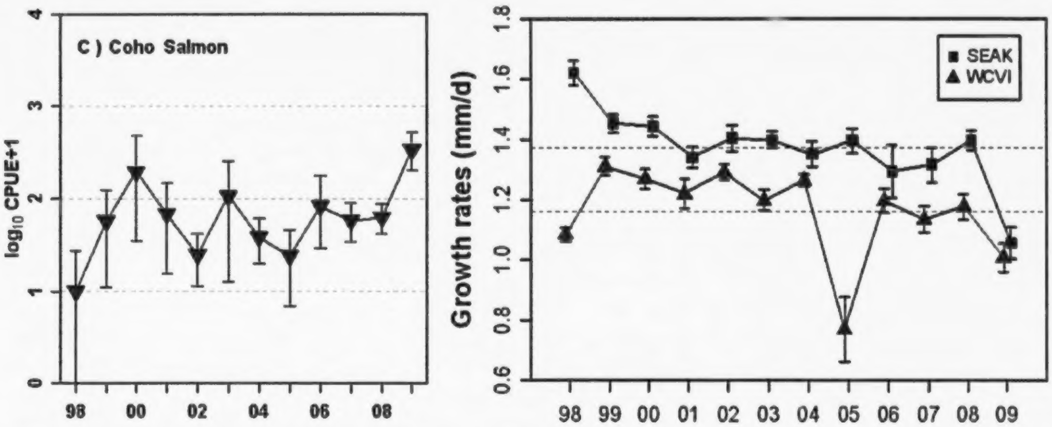


Figure 8. (left). Catch-per-unit-effort (CPUE) of Coho salmon off the west coast of Vancouver Island in June-July 1998-2009. Average CPUE and 95% confidence intervals were obtained by bootstrapping. (right) Growth rates (May-October) of juvenile Coho salmon off the west coast of Vancouver Island (red triangles, WCVI) and Southeast Alaska (blue squares, SEAK). The blue and red dotted lines represent the 1998-2009 average values for Southeast Alaska and the west coast of Vancouver Island, respectively. The error bars are 2 times the standard error. (Contributed by Marc Trudel of DFO.)

It is important to realize that good survivals do not necessarily mean good returns. Coho salmon that will return in 2010 are the progeny of smolts that went to sea in the warm spring of 2006, many of which experienced low marine survivals, producing low spawning escapements in 2007. Even with relatively high survivals, returns in 2010 are expected to be modest because of the low spawner numbers in 2007.

Abundance of the WCVI herring stock in 2009 was similar to low levels observed since 2006 and remained well below the fishery threshold. Herring take several years to reach a size suitable for fisheries (denoted as recruitment), so their availability to fisheries is largely determined by ocean factors in the years prior to recruitment. Research has shown that recruitment of WCVI herring tends to be negatively correlated with increasing temperatures, probably reflecting: 1) poor feeding conditions for young herring during their first growing season; and 2) increased mortality from predation in warm years. Studies investigating predation rates indicate that the negative correlation between herring recruitment and hake biomass could be caused by predation or competition for food. Ocean conditions were warmer in 2002-2005, impacting herring survival, resulting in reduced biomass and recruitment. However, cooler conditions, since 2006, and declining hake abundance should improve herring recruitment in the future.

Pacific sardine provide another example of a delayed response to temperature. Pacific sardine is a migratory species, moving annually between spawning grounds in southern California to the rich feeding areas off the west coast of Vancouver Island. The sardine fishery in Canadian waters collapsed in 1947. Sardines reappeared off the west coast of Vancouver Island in 1992. From 1992 to 1996, their distribution was limited to the south-western portion of Vancouver Island. In the very warm summer of 1997, their distribution expanded northward, and by 1998, sardines extended into central and northern BC waters. In 2003 and 2004 the distribution of sardines in BC was limited to the inlets of Vancouver Island and offshore areas in the south, following the general cooling of BC waters from 1999-2002. Warm conditions in 2002-2006 and a very strong 2003 year-class resulted in widespread distribution of sardines throughout southern Hecate Strait and Queen Charlotte Sound.

Albacore tuna appear close to Canada's west coast when waters are warm. June sea surface temperature (SST) anomalies at Amphitrite Point are used as a predictor of the availability of "tuna waters". The two graphs at left show this link between tuna catch and ocean temperature. Unlike other species, it is the migratory juveniles and adults that respond to ocean temperature.

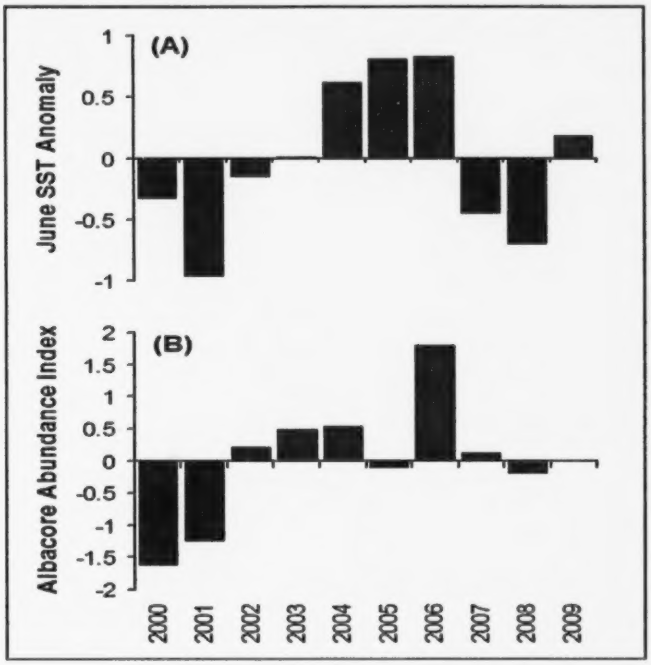


Figure 9. June sea surface temperature (SST) anomalies at Amphitrite Point on the SW coast of Vancouver Island (A) and annual abundance index values (standardized albacore catch rate anomalies) in BC waters (B). Zero in both figures represents average conditions for the 1971-2000 (SST) and 2000-2008 (catch rates) periods. (Contributed by John Holmes of DFO.)

Marine life outside the WCVI sometimes appear to be relatively insensitive to temperature changes. This may not be the case, however. There can be significant time lags before effects are noticeable. Improved understanding of linkages between biology and physics are needed.

UPDATES ON THE PACIFIC NORTH COAST

The Pacific North Coast Integrated Management Area (PNCIMA) of British Columbia lies in northern Pacific Canadian waters as far south as Campbell River in the Strait of Georgia and Brooks Peninsula on the outer coast (Figure 10.)

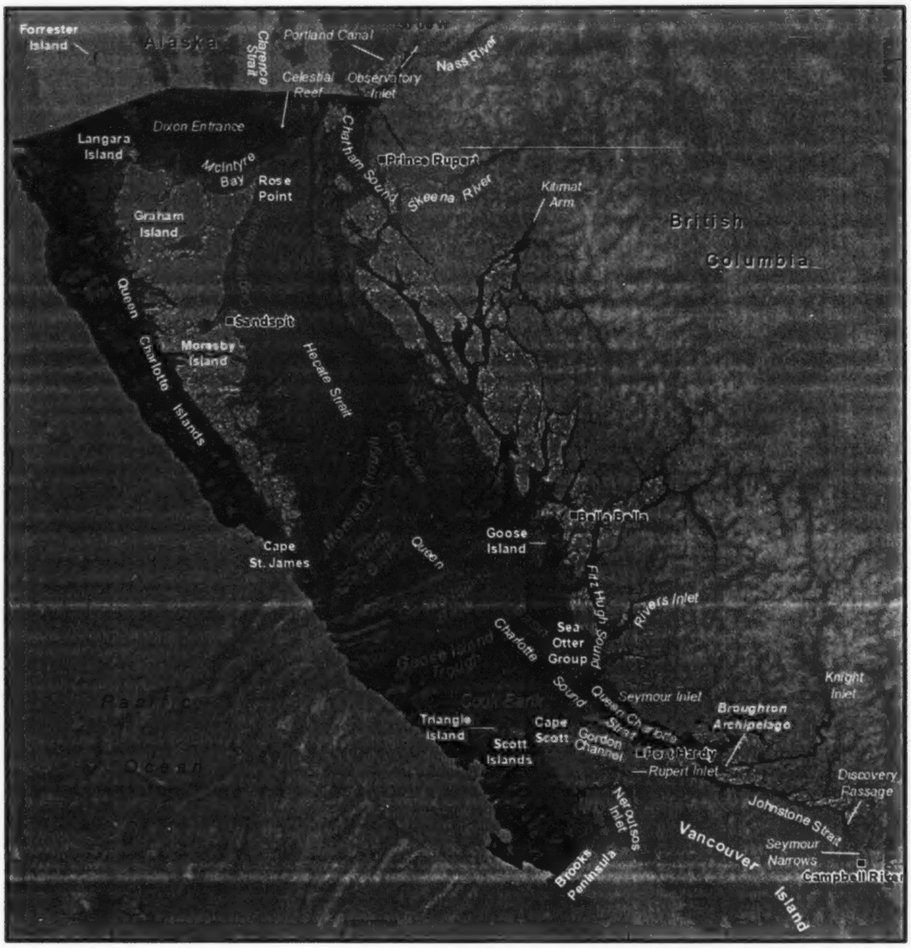


Figure 10. The Pacific North Coast Integrated Management Area (PNCIMA), one of five large ocean management areas established for ecosystem-based management across Canada. Figure from Lucas, B.G., Verrin, S., and Brown, R. (Editors). 2007. Ecosystem overview: Pacific North Coast Integrated Management Area (PNCIMA). Can. Tech. Rep. Fish. Aquat. Sci. 2667: xiii + 104 p.

This region holds the richest groundfish and Dungeness crab fisheries in BC, and is also a major route for cruise ships in spring and summer. Although the population density is far lower than in southern British Columbia, its residents tend to be more connected spiritually and economically to the ocean and its life.

The following summarizes some of the results included in this year's report on the PNCIMA region. Next year we hope to devote more time to this important region, and we expect our coverage to be more complete.

Temperature changes

The ocean has been cool for the past few years, and unlike in southern British Columbia where lighthouse records reveal warming in the second half of 2009, most PNCIMA lighthouse records indicate temperatures remained cool through the year (Fig. 11).

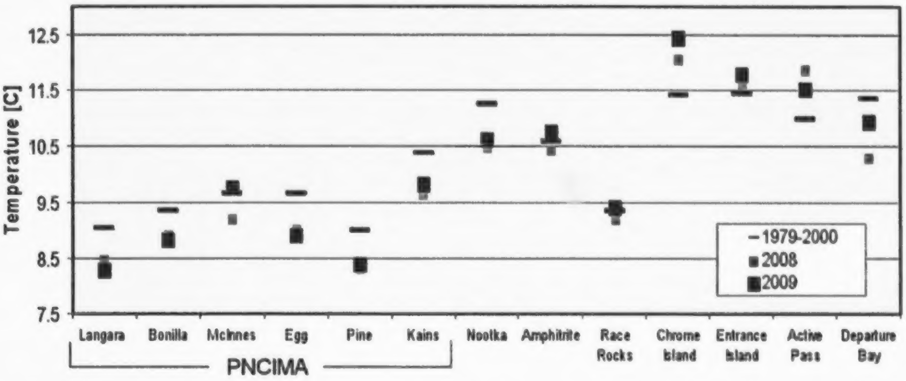


Figure 11 The mean daily sea surface temperature in 2008 and 2009 at BC lighthouse stations, and the annual mean calculated from 1979-2000 data. The first six stations (from the left) are within PNCIMA. (Contributed by Peter Chandler of DFO.)

Temperatures were below normal in all six PNCIMA lighthouse records in 2008, and in five of the six in 2009, (Fig. 11). By comparison, only two stations in BC to the south of PNCIMA were significantly below normal in 2008 and 2009: Nootka and Departure Bay.

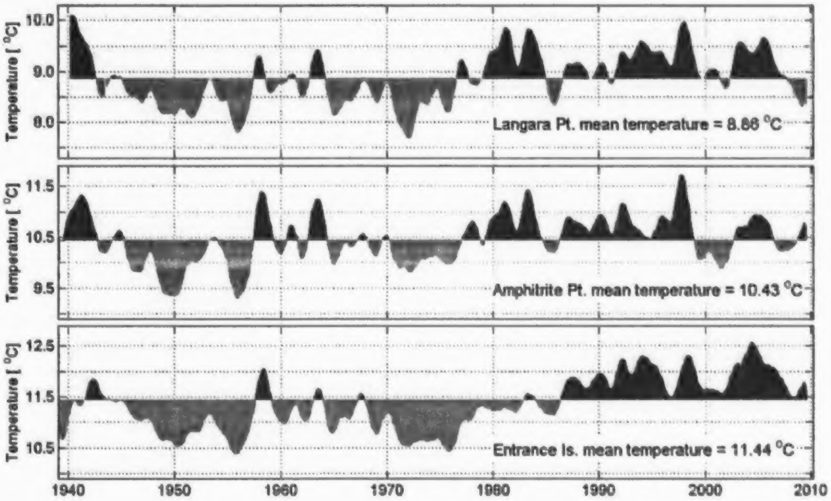


Figure 12 Temperature records at Langara Island, Amphitrite Point, and Entrance Island, where daily tempera-ture and salinity samples are collected as part of a long-term lighthouse sampling program by DFO. (Contributed by Peter Chandler of DFO.)

This cooling in PNCIMA, in 2008 and 2009, is clearly unusual when compared to previous decades, as shown in the graph above (Fig. 12) for three lighthouse records in British Columbia. The top graph shows that the ocean waters at Langara Island, off the NW tip of the Queen Charlotte Islands, were cooler in 2008 and 2009 than observed at any time since the mid-1980s. In contrast, waters at Amphitrite Point (west coast of Vancouver Island) and Entrance Island

(Strait of Georgia) began to warm in 2009; note that all three stations in Figure 12 reveal warming from the 1950s to present, a feature shared by most global temperature records.

Zooplankton

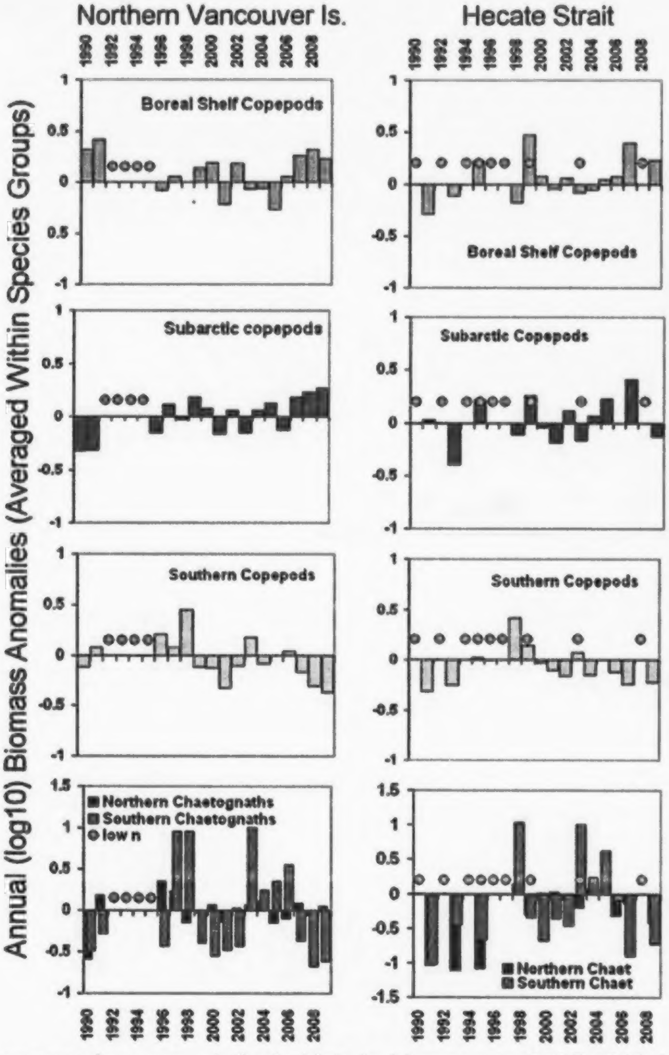


Figure 13 (below) Zooplankton time series sampling locations (red dots) off the BC continental margin. Data are averaged within major statistical areas indicated by ovals

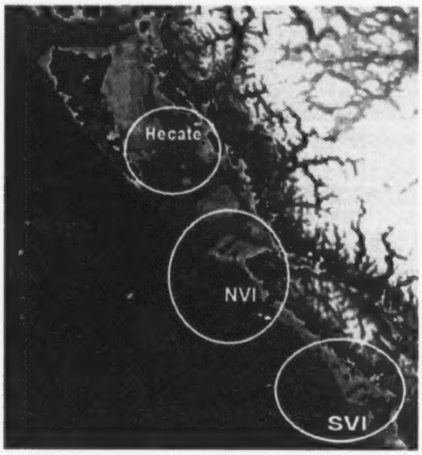


Fig. 14 (left). Zooplankton species-group anomaly time series for two regions in PNCIMA. Bar graphs are annual log scale anomalies. Circles indicate years with no or very few samples from that region. Cool years favor endemic 'northern' taxa, warm years favor colonization by 'southern' taxa. (Contributed by Dave Mackas, DFO.)

As discussed earlier, temperature largely determines the zooplankton species that dominate our coastal waters. Figure 14 reveals that cool-water, boreal shelf copepods were relatively high in biomass in 2007-2009 in northern Vancouver Island and in Hecate Strait compared to previous warm years. Subarctic copepods, another cool-water group, were dominant in 2007-2009 in northern Vancouver Island and in 2007 in Hecate Strait. No data are available for 2008 for Hecate Strait. As expected for years of cool ocean waters, a lower biomass of southern copepods occurred in 2007-2009 in both regions. Among the species of chaetognaths, it was the southern ones that declined in the cool years of 2007-2009 in northern Vancouver Island and Hecate Strait. Chaetognaths and jellyfish are the dominant carnivorous zooplankton. It is assumed that when northern, cool-water zooplankton dominate, plankton-feeding animals will benefit from this energy rich food source compared to when southern, warm-water species dominate.

Herring

Herring in the Hecate Strait area represent a combination of three major migratory stocks: the Queen Charlotte Islands stock, the Prince Rupert stock, and the Central Coast stock. Over the past decade, abundance of the Queen Charlotte Islands stock (Figure 15a) has been depressed whereas abundance of both Prince Rupert and the Central Coast stocks have remained stable (Figures 15b and c). Recruitment to the Queen Charlotte Islands stock has been depressed, with only two 'good' year-classes out of the past ten, while the Prince Rupert stock has experienced a 'good' recruitment at least every four years since 1980.

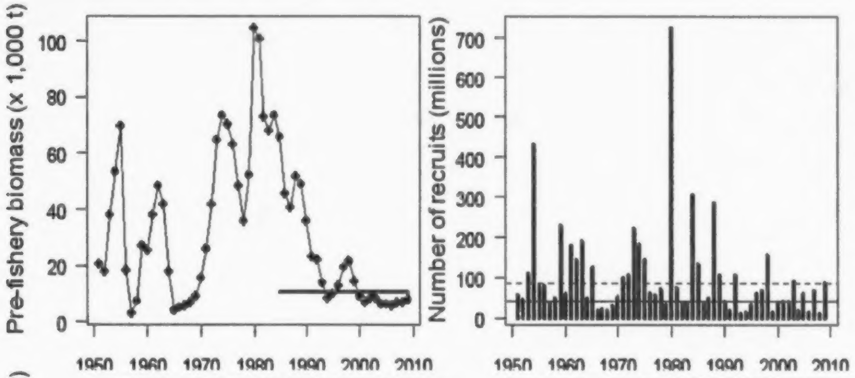


Figure 15a. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Queen Charlotte Islands herring stock. Note that 2 of the last 10 years have seen 'good' recruitment.

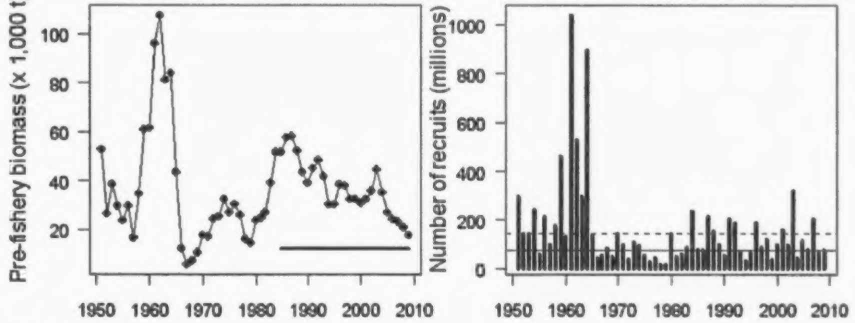


Figure 15b. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Prince Rupert District herring stock. Note that 'good' recruitments have occurred almost every four years since 1980.

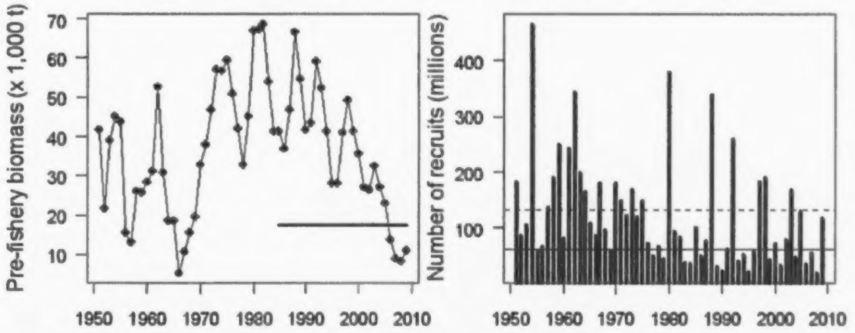


Figure 15c. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Central Coast herring stock.

In the three figures above, the solid horizontal line in the left panel denotes the commercial fishing cutoff (i.e. no fishing when estimated biomass below this level). In the right panel the boundary for 'poor'-'average' recruitment is indicated by a solid line, and the boundary for 'average'- 'good' recruitment is indicated by a dashed line. Recruitment to the Central Coast stock (Figure 15c) has been less regular but the 'good' year-classes that have occurred were very strong.

Indications are that the most recent recruitments (2003-2005 year-classes) are 'poor' or 'average', resulting in declines all three PNCIMA herring stocks. Cool conditions in 2006 resulted in improved recruitment and slight increases in abundance in all three areas. Declining hake abundance may result in improved herring recruitment in this area in the short term.

Chinook salmon

Under the jurisdiction of the Pacific Salmon Treaty (PST), 30 Chinook salmon stock aggregates and 25 fisheries distributed between southeast Alaska and northern Oregon are managed annually to either projected landed catch targets or are limited by maximum allowed exploitation rates. Estimates of escapements or terminal runs of mature fish for each of the stock aggregates and estimates of numbers of Chinook landed or released in the PST fisheries are assembled annually and provide some of the crucial data inputs to the calibration of the Coast-wide Chinook Model (CM). The Chinook stocks (consisting of both wild- and hatchery-origin fish) and fisheries represent nearly all Chinook and fishing-related impacts known to occur within the PST jurisdiction.

Time series of abundance indices (AIs) are annually derived and reported to the Pacific Salmon Commission in technical reports prepared by the bilateral Chinook Technical Committee (e.g., TCCHINOOK 09(1), 2009 Annual Report of Catches and Escapements, TCCHINOOK 09(3), 2009 Annual Report of Exploitation Rate Analysis and Model Calibration available at http://www.psc.org/publications_tech_techcommitteereport.htm#TCCHINOOK).

The AIs are derived by dividing the annual estimated Chinook abundance, in any one fishery, by the average from the 1979-1982 'base period'. These provide a means to assess temporal and spatial trends in the relative abundance of Chinook stocks contributing to regional fisheries. Figure 16 presents time series of the three northern groups, which include two within PNCIMA (Northern BC and Central BC). Chinook appear to be rebounding from the low numbers in 2008, and predictions suggest an increase in 2010 from 2009.

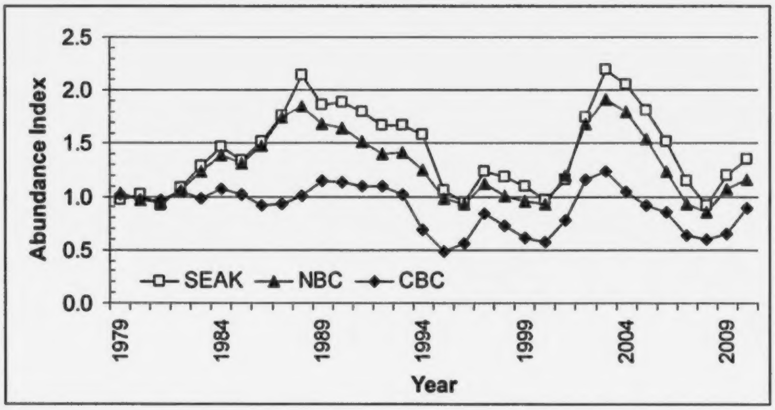


Figure 16. Time series of Chinook salmon abundance indices for three major northerly PST fisheries, 1979-2010. The fisheries are southeast Alaska troll (SEAK), northern BC troll (NBC) and central BC troll. Please note that 2010 values are forecasts resulting from the March 2010 calibration of the Coast-wide Chinook Model. (Contributed by Gayle Brown of DFO)

PHYTOPLANKTON BLOOMS IN THE STRAIT OF GEORGIA

We use the high spatial resolution of MERIS and MODIS satellite imagery to monitor chlorophyll concentrations along the BC coast. Availability of the higher resolution MERIS imagery (300m) has recently been improved by upgrades to Canadian satellite receiving stations.

In February and March of the years 2001-2009, MERIS and MODIS imagery showed a chlorophyll pattern recurring in three years out of nine, which suggests seeding of the early spring bloom in the Strait of Georgia from deep, glacial inlets to the north. High chlorophyll values are first observed in Jervis and Sechelt inlets in mid-February, then in Malaspina Strait, an arm of the Strait of Georgia, before spreading across the main body of the Strait in late February and early March.

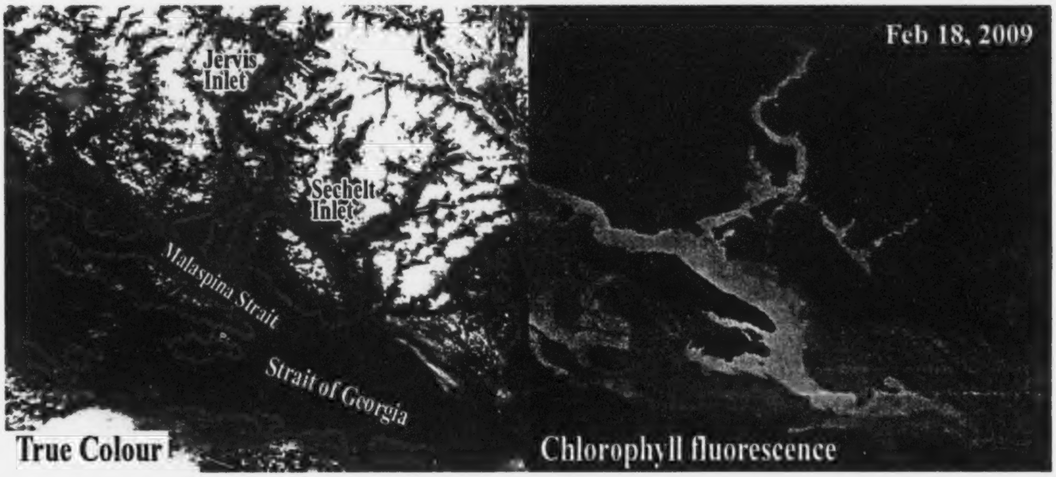


Figure 17. MERIS full resolution (300 m) images for 18 February 2009 for the central Strait of Georgia and Jervis and Sechelt Inlets to the north. The true-colour image (left) shows snow over high elevations on land, cloud cover and a digital coastline. The chlorophyll fluorescence image (right) shows ocean surface chlorophyll, here with the "Malaspina Dragon" pattern due to a bloom from Jervis Inlet entering the Strait. The name derives from its dragon-like shape, with head at lower right, tail at top left. Low chlorophyll values are shown in blue. Higher values are shown in green, yellow and orange. Land and clouds are coloured black.

We call the pattern the "Malaspina Dragon" after its shape in satellite imagery in 2005, 2008 and 2009 shortly after it entered the Strai (Fig. 17). It appears that the main spring bloom in the Strait of Georgia occurs earlier in years when the Dragon is present, suggesting that seeding from inlets in some years should be added to the list of factors controlling timing of the main spring phytoplankton bloom in the Strait of Georgia.

The first spring measurements of chlorophyll by sampling from research vessels are normally in April. Ship-based measurements reveal that chlorophyll concentrations in the Strait of Georgia in April 2009 were the highest observed in any survey since regular measurements began in 2002. Chlorophyll concentrations in April 2009 reached concentrations of >40 mg m^3 in the surface layer. In comparison, spring chlorophyll concentrations in Juan de Fuca Strait were similar to previous years (<3 mg m^3). Chlorophyll is an indicator of phytoplankton biomass, so from these measurements we can estimate the availability of plant food for the entire marine food chain. In general, nitrate concentrations are lower and phytoplankton biomass is higher in the Strait of Georgia than elsewhere in this region. Seasonally, chlorophyll concentrations in the

Strait of Georgia are highest during the spring bloom (March-April), low during the summer, increasing again at the end of the summer/early fall, and lowest during winter.

In contrast, in Juan de Fuca Strait, chlorophyll concentrations are usually lower than in the Strait of Georgia and remain generally low all year (<3 mg m^3). In summer 2009, however, upper layer (0-15 m) chlorophyll concentrations in Juan de Fuca Strait were unusually high (> 5 mg m^3) compared to previous years (2002-2008), and higher than those measured in the Strait of Georgia. At the same time, upper layer (0-15 m) nitrate concentrations in Juan de Fuca Strait and at the northern end of the Strait of Georgia were lower than those observed in June of the seven previous years.

CONTAMINANTS IN BOTTOM SEDIMENTS

Once a contaminant has been banned on land, it can continue to cycle through the ocean and marine sediments for decades as a legacy contaminant. Polychlorinated biphenyls (PCBs), for example, were banned in stages commencing in the early 1970s, but continue to present a significant threat to marine biota, including killer whales. Lead in gasoline is another.

The concentration of PCBs in the sediment of the Strait of Georgia is decreasing with time due to reduced PCB contamination in recent sediments, but active benthic mixing keeps the surface sediment concentration high by recycling deeper, more contaminated sediments. Concentrations of lead are following a similar trend.

In contrast to PCBs, the concentration of flame retardant polybrominated diphenyl ethers (PBDEs) is increasing rapidly in sediment (Figure 18).

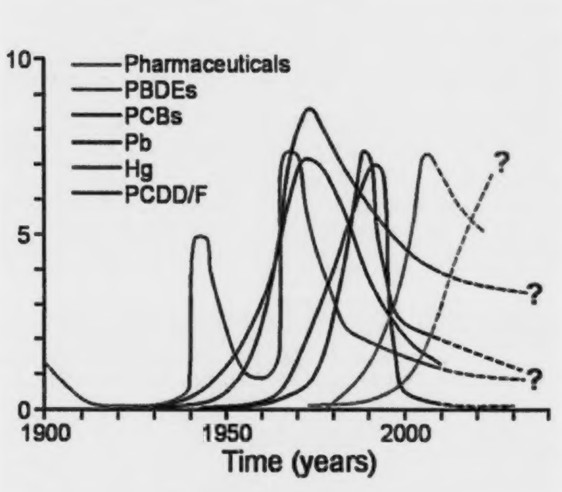


Figure 18. A conceptual presentation of contaminant loading histories to the Strait of Georgia. Pb=lead, Hg=mercury; PCDD/F =polychlorinated dibenzo dioxins/furans. The timing on the x-axis is approximately correct, but there are no units on the y-axis, because the fluxes of the various contaminants span several orders of magnitude. Contributed by S. Johannessen of DFO.

APPENDIX 1 AGENDA

State of the Ocean Meeting at Pacific Biological Station Seminar Room, Nanaimo
Wed. 17 Feb. 2010

1000	Introductions; review agenda
1015	*Climate Indices, and mostly Gulf of Alaska*
Bill Crawford	Global and Gulf of Alaska weather and ocean conditions
Marie Robert	Gulf of Alaska as seen along Line P
Howard Freeland	Argo views of variability in the Gulf of Alaska
Frank Whitney	Nutrients in the NE Pacific, UVic VENUS update
Jim Gower	Remote sensing of Gulf of Alaska and BC waters
Jennifer Bolt	Gulf of Alaska from the Alaskan perspective
Sonia Batten	Zooplankton in the Gulf of Alaska from CPR observations
John Holmes	Albacore tuna
1200 Lunch	
1300	*Mostly West Coast*
Roy Hourston	Winds and currents along the outer coast (with R. Thomson)
Peter Chandler	Temperatures and salinities at light-stations
Greg Workman	Oxygen and temperature collected from groundfish trawl surveys
Dave Mackas	Zooplankton along the outer coast
Ron Tanasichuk	Euphausids
Ian Perry	Small-mesh multi-species surveys
All scientists	Discussion
1500-1530 Break	
1530-1730	*Mostly West Coast (continued)*
Steve Diggon	PNCIMA Reporting
Kim Hyatt	Sockeye indicator-stock performance and survival
Yuri Zharikov	Observations in the Pacific Rim National Park Reserve
Linda Nichol	Trends in distribution for BC baleen whales
Kathryn Wallace	Barkley Sound research (Speaking for Tom Oakey)
All scientists	Discussion

Thurs. 18 Feb. 2009

0830	*Mostly Georgia Basin*
Graham Gillespie	Humboldt squid
Jake Schweigert	Forage Fish
Sophie Johannessen	Contaminants in Strait of Georgia.
Angelica Peña	Phytoplankton observations
Susan Allen	Strait of Georgia spring bloom timing
David Welch	Measurements of salmon smolt survival in Strait of Georgia & outer coast
1000-1030 Break	

1030-1200	*West Coast & Strait of Georgia*
Bill Peterson	Ocean ecosystem indicators of salmon marine survival in the N. California current over the past decade: how 2009 compared to previous years
Rusty Sweeting	Juvenile salmon in Strait of Georgia as observed in June and September (with K. Lange, R. Beamish and C. Neville)
David Preikshot	Strait of Georgia salmon and wind speed covariability
Sue Grant	Fraser Sockeye productivity
Marc Trudel	Juvenile salmon on the continental shelf of BC and Alaska
1200	Lunch
1300	
Jim Irvine	Coho, Sockeye, and oceanographic indicators (with G. Borstad, L. Brown, D. Blackbourn, L. Godbout & R. Thomson) and highlights from the 16 Feb. salmon workshop
Chuck Parken	Chinook trends in coast-wide fisheries (with Gayle Brown)
Veronica Lo	Climate Change Impacts on Canada's Pacific North Coast
1415	Discussion of key results overall and synthesis
1530 h	Adjourn

APPENDIX 2 CONTRIBUTORS TO THIS REPORT

Susan Allen	UBC
Sonia Batten	SAHFOS
Richard Beamish	DFO
David Blackbourn	Contr
Jennifer Boldt	DFO
Gary Borstad	ASL-B
Jim Boutillier	DFO
Gayle Brown	DFO
Leslie Brown	ASL-B
John Candy	DFO
Kai M.A. Chan	UBC
Peter Chandler	DFO
Peter Clarkson	PC
Jaclyn Cleary	DFO
Ken Cooke	DFO
William Crawford	DFO
Patrick Cummins	DFO
Deborah Faust	DFO
Howard Freeland	DFO
Moira Galbraith	DFO
Graham Gillespie	DFO
Lyse Godbout	DFO
Jim Gower,	DFO
Chris Grandin	DFO
Sue Grant	DFO
Bob Hansen	PC
Mark Hipfner	EC
John Holmes	DFO
Roy Hourston	Contr - ACM
James Irvine	DFO
Sophia Johannessen	DFO
Yeongha Jung	DFO
Stephanie King	Contr
Krysta Lange	DFO
Colin Levings	DFO
Doug Latornell	UBC
Dawn Lewis	DFO
Veronica Lo	CPAWS
Rob Macdonald	DFO
Dave Mackas	DFO
Diane Masson	DFO
Catherine Michielsens	PSC
John Morris,	DFO
John Morrison	VDI
Chrys Neville	DFO
Charles Parken	DFO
Angelica Peña	DFO
Ian Perry	DFO
Bill Peterson	NFSC
Dennis Rutherford	DFO
Jake Schweigert	DFO
Ruston Sweeting	DFO
Ron Tanasichuk	DFO
Mary Thiess	DFO
Richard Thomson,	DFO
Marc Trudel	DFO
Strahan Tucker	DFO
Antonio Velez-Espino	DFO
David W. Welch	KRC
Frank Whitney	DFO
Megan Wolfe	UBC
Yuri Zharikov	PC
Tyler Zubkowski	DFO

Report edited by William Crawford and James Irvine

ACM	Accredited Consultant Meteorologist
ASL-B	ASL Borstad Remote Sensing Inc.
Contr	Private Contractor
CPAWS	Canadian Parks and Wilderness Society
DFO	Fisheries and Oceans Canada
EC	Environment Canada
KRC	Kintama Research Corporation
NFSC	Northwest Fisheries Science Centre, NOAA, USA
PC	Parks Canada
PSC	Pacific Salmon Commission
SAHFOS	Sir Alister Hardy Foundation for Ocean Science, UK
VDI	Vynx Design Inc

APPENDIX 3 – INDIVIDUAL REPORTS

GLOBAL AND NORTH PACIFIC CONDITIONS

TEMPERATURES IN 2009: GLOBALLY WARM BUT LOCALLY COOL

Bill Crawford, Fisheries and Oceans Canada

The average temperature in 2009 was warmer than average almost everywhere on land and ocean, but was cooler off the west coast of Canada. The map below shows where temperatures were warmer (red) or cooler (blue) than in past years. When averaged over all of 2009, northern Canada and Siberia were several degrees above average, but Pacific Ocean waters west of British Columbia were actually cooler. This local cooling also showed up in 2007 and 2008, part of a Pacific-wide weather pattern during La Niña conditions of these years. Local ocean waters warmed greatly in early 2010.

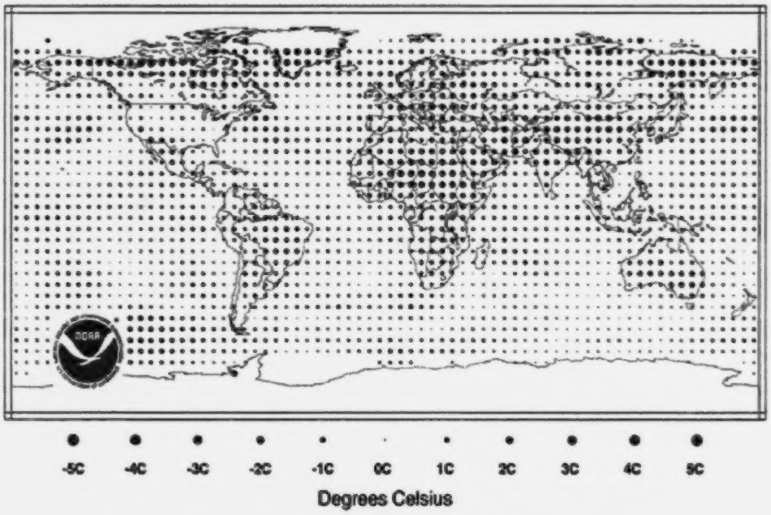


Figure 1. Annual surface temperature anomaly for 2009 (°C). relative to 1971 to 2000. Image provided by the National Climate Data Center of NOAA, the US National Oceanic and Atmospheric Administration.

The long term global temperature trend is shown below in Figure 2. The year 2009 was one of the warmest, and the decade of 2000 to 2009 was the warmest since 1880 when reliable records began.

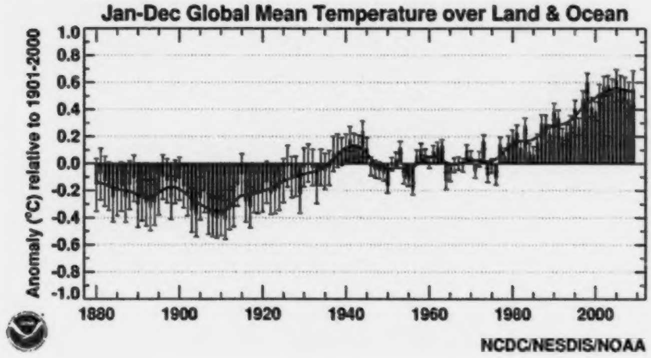


Figure 2. Changes in global temperatures since 1880, relative to the 20th century average. Graph provided by the National Climate Data Center of NOAA.

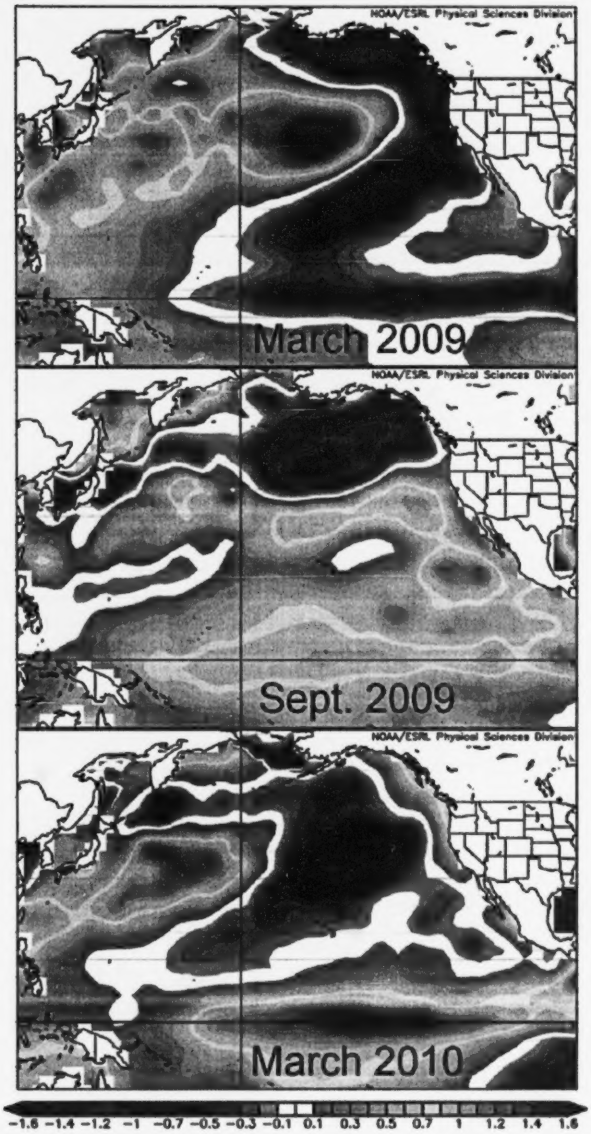

NOAA/ESRL Physical Sciences Division
March 2009
NOAA/ESRL Physical Sciences Division
Sept. 2009
NOAA/ESRL Physical Sciences Division
March 2010
−1.6 −1.4 −1.2 −1 −0.7 −0.5 −0.3 −0.1 0.1 0.3 0.5 0.7 1 1.2 1.4 1.6

Figure 3. Ocean temperature anomalies in the Pacific Ocean. The map extends from North America to Asia, and from 65°North to 15°South. The Equator is marked by a horizontal black line in each panel; The vertical black line is at 180°W. The temperature anomaly scale (at bottom) extends from minus 1.6°C in purple to plus 1.6°C in dark red. Images provided by NOAA Earth System Research Laboratory.

The changes of ocean temperatures in the Pacific Ocean can be seen in the three panels of Figure 3 at left. These maps present temperature anomalies of March and September 2009 and March 2009.

The cold (purple) oceans west of North America in March 2009 were also present all through 2008. By September 2009 this pool of cooler-than-normal water moved to the west, allowing a patch of warmer-than-normal water to extend north along the North American coast to Vancouver Island. By March 2010 this warm pool enclosed all of the west coast of USA and Canada.

Accompanying this shift was an increase in temperature all along the Pacific Equator, part of the shift in weather from La Niña to El Niño in May 2009. El Niño is formally defined by the ocean temperature along the Equator in the Pacific Ocean, and is present when these temperatures exceed 0.5°C above normal for one to two seasons. La Niña takes place when temperatures fall to more than 0.5°C below normal.

Temperatures in March 2009 were similar to those of March 2008, and were typical of winters with La Niña conditions in the Pacific Ocean, with relatively cool waters along the eastern Equator and along the west coast of North America. These ocean temperatures are usually set up by stronger trade winds over the tropical North Pacific Ocean and stronger westerly winds in the subarctic North Pacific. Similarly, Pacific Ocean temperatures of early 2010 were typical of El Niño winters, with warm oceans along the North American west coast. Air temperatures warmed up as well in British Columbia, melting snow on ski runs prior to the start of the 2010 Vancouver Winter Games.

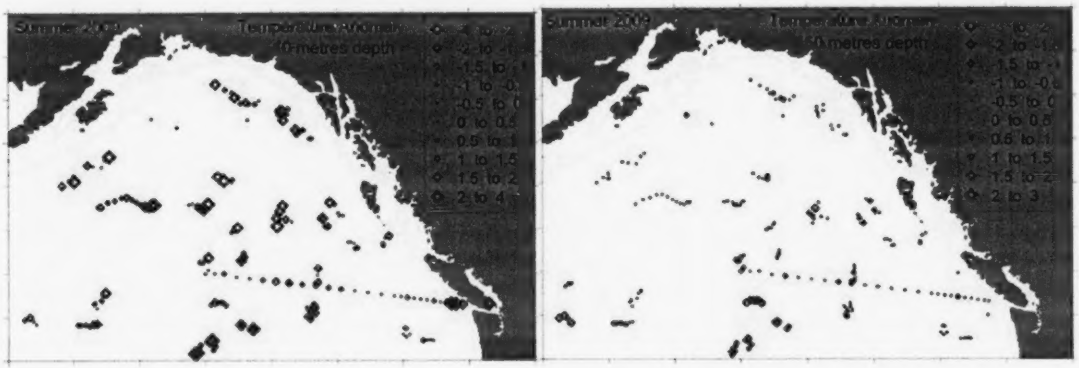


Figure 4. Anomalies of ocean temperature (°C) in Gulf of Alaska in summer 2009 (August and September) at 10 metres depth (left panel) and 150 m depth (right panel), referenced to average temperatures from 1929 to 2005. Symbols show temperature measured by Argo profilers or by scientists on the Line P research cruise. Symbol colour denotes whether positive anomaly (red) or negative (blue). Size of each symbol denotes magnitude of the anomaly according to the scale in each panel.

The maps of all the individual temperature measurements in August to September 2009 reveal cool offshore regions of the Gulf of Alaska waters at the ocean surface (10 m depth in left panel of Fig. 4). These waters have remained well below normal temperature since 2007, associated with large scale, persistent weather patterns of La Niña. This cooling reached several degrees Celsius at many locations in summer. Warmer waters appeared closer to Vancouver Island by mid-2009, for the first time in several years. At 150 m depth (right panel in Figure 4) the waters over the most of the gulf are actually warmer than normal, with more warming in the southern gulf, perhaps associated with stronger flow of the North Pacific Current. Only close to the Queen Charlotte Islands are temperatures at 150 metres depth cooler than normal.

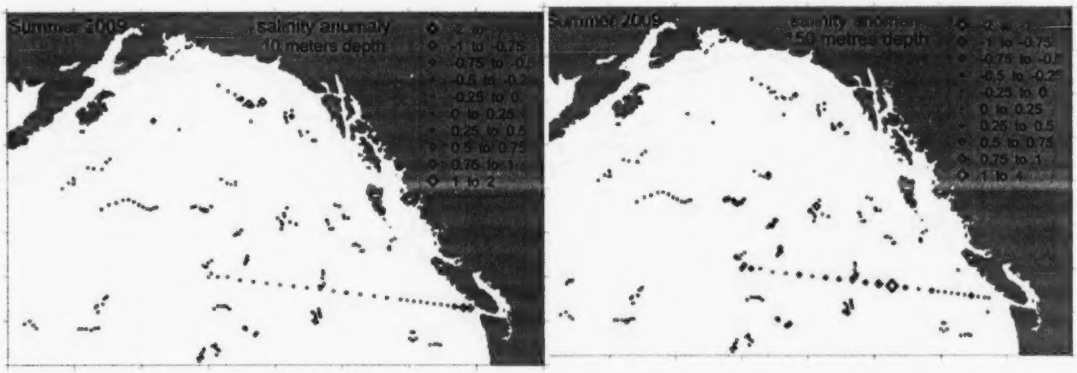


Figure 5. Anomalies of ocean salinity in summer 2009 (August and September) at 10 metres depth (left panel) and 150 m depth (right), referenced to 1929 to 2005. Each symbol represents temperature measured by Argo profilers or by scientists on the Line P research cruise. The colour of each symbol denotes whether positive anomaly (red) or negative (blue). Size of each symbol denotes magnitude of the anomaly according to the scale in each panel.

Salinity measurements at 10 metres depth (left panel of Fig. 5 above) reveal saltier waters (positive anomalies) close to the Canadian coast and fresher waters farther offshore, in central regions of the Gulf of Alaska. This freshening in the middle of the gulf is even stronger at 150 metres depth (right panel above).

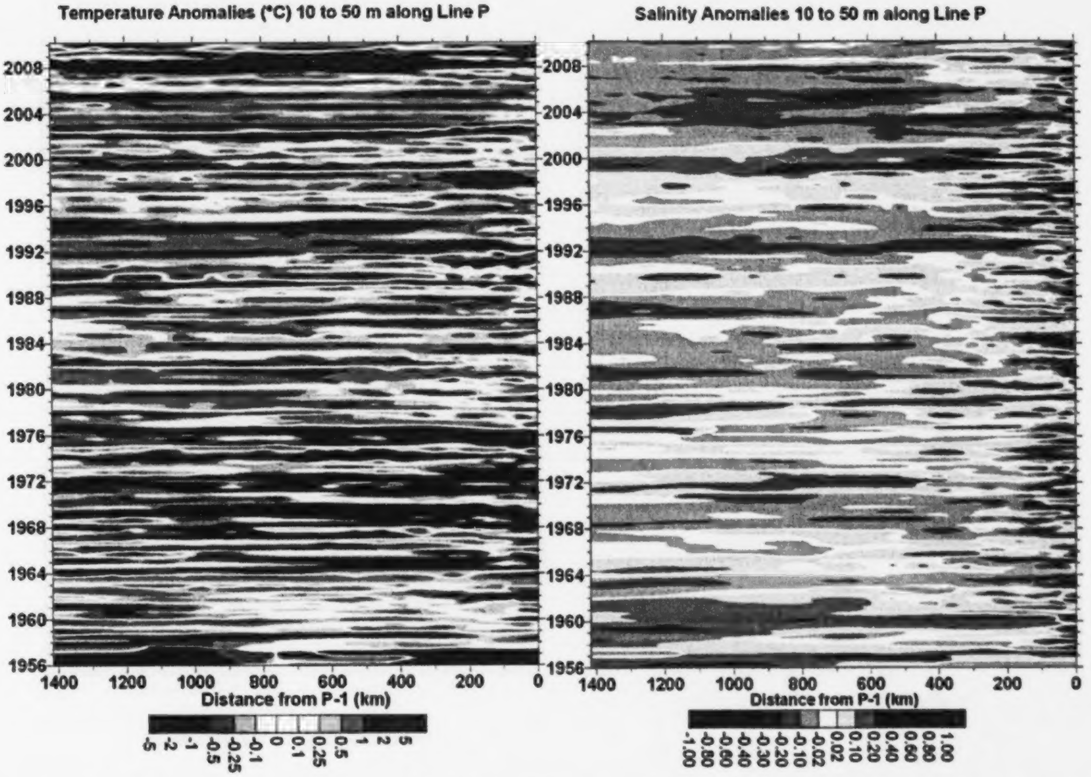


Figure 6. Time-distance plot of anomalies of temperature (°C left and salinity right) along Line P, which is a set of ocean stations extending from the western entrance of Juan de Fuca Strait to Ocean Station Papa at 50°N, 145°W in the Gulf of Alaska. Scale bars are below each panel. The horizontal axis denotes distance west of from Station P1 on the continental shelf of Vancouver Island near Juan de Fuca Strait. Vertical axes present the year of the anomalies.

Temperature in the top layer of the Gulf of Alaska generally remains warm or cool for several years or even decades. The graph at top left shows these persistent anomalies by presenting different colours to show ocean temperature above normal (red) or below normal (blue) along a 1500-km-long swath across the gulf, starting in the year 1956 at bottom, and ending in February 2010 at top. The Canadian coast is at the right of each panel, with deep-sea waters at left. This graph is based on more than 50 years of scientific measurements along Line P, a set of sampling stations maintained by Fisheries and Oceans Canada, and one of the longest such records in the world.

The ocean surface warming in early 2010 appears as a shift from blue to red at the very top of the left graph. Temperatures were well below normal from 2007 to 2009, as indicated by the deep blue shading for these years. More noticeable is the blue-to-red shift in 1977, which marked a Pacific-wide change in ocean temperature, and the beginning of more rapid global warming that persisted until late 1990s.

Salinity anomalies were not nearly as extreme as the temperature anomalies, although the relatively fresh conditions (negative anomalies in blue) since 2001 beyond 200 km from shore continue to persist at depths of 10 to 50 metres all along Line P.

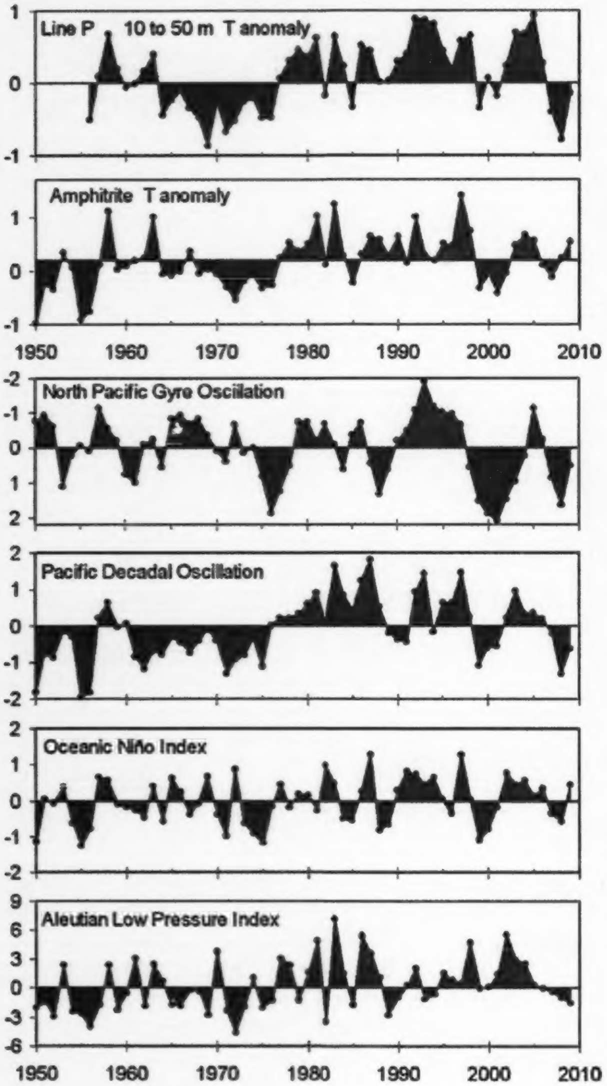


Figure 7 at left displays a set time series representing climate of the North Pacific Ocean plus the El Niño – Southern Oscillation (ONI). All time series are plotted as anomalies relative to average. The North Pacific Gyre Oscillation is inverted so its anomalies align with other series.

The figure at left shows how warm waters close to the North American west coast are related to large-scale features of the Pacific Ocean. The top two graphs show temperature averaged along Line P (see Fig. 6) and at Amphitrite Point on the west coast of Vancouver Island. These temperature anomalies tracked each other well until 2007, when the waters along Line P cooled more than at the Vancouver Island shore.

The North Pacific Gyre Oscillation (NPGO) and the Pacific Decadal Oscillation (PDO) are patterns of ocean temperature that cover the entire North Pacific Ocean. They are often associated with El Niño and La Niña, as represented by the Oceanic Niño Index (ONI). Positive ONI indicates El Niño, negative is La Niña. In general, warming near the Canadian west coast (red regions) aligns with positive ONI, PDO and Aleutian Low Pressure Index, and negative NPGO.

Note that almost all these time series shifted toward "red" in 2009. Only the Aleutian Low Pressure Index headed more into the blue, because it is defined by winter temperatures only, and did not pick up the shift to El Niño in the spring on 2009. The Aleutian Low Pressure Index (ALPI) tracks the area enclosed in winter by the Aleutian Low Pressure System. In general, Aleutian Lows are larger in area and lower in air pressure during El Niño winters, bringing warmer conditions to the west coast of Oregon to British Columbia. Since 1976 this low has been larger in area than it was prior to 1976. The PDO was discovered in mid 1990s, and upon tracking it back through the 20th century, scientists noticed that temperatures in the eastern Gulf of Alaska were generally warmer when positive PDO coincided with El Niño

(+ve ONI). From the 1960s to late 1990s, the PDO seemed to be a better indicator of Pacific west coast ocean temperature than El Niño. However, for the past ten years the PDO and ONI have seen about the same changes in time, and we have been able to predict changes in ocean temperature in the eastern Gulf of Alaska by watching the ONI index. It shifted from negative to positive in mid-2009, and local waters warmed by several degrees along the west coast about six months later, in early 2010.

Sources of information on climate indices

Line P temperature anomalies are based on Crawford et al. (2007) and are available at: http://www-sci.pac.dfo-mpo.gc.ca/osap/data/linep/linepselectdata_e.htm.

Crawford, W. R., Galbraith, J., Bolingbroke, N., 2007: Line P ocean temperature and salinity, 1956-2005. *Progress in Oceanography*, **75,** 161-178, doi:10.1016/j.pocean.2007.08.017.

Amphitrite temperature anomaly time series are based ocean surface temperatures measured daily at the Amphitrite Lightstation. Reference years are 1971 to 2000. The time series is provided by Fisheries and Oceans Canada at this Internet site:
http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/Searchlighthouse_e.htm

Pacific Decadal Oscillation (PDO) is based on analysis of Mantua et al. (1997) and Zhang et al. (1997). The time series was provided at this Internet site of the Joint Institute for Studies of Atmosphere and Ocean of NOAA in Seattle: http://jisao.washington.edu/pdo/PDO.latest

Mantua, N.J. and S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis,1997: A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78, pp. 1069-1079.

Zhang, Y., J.M. Wallace, D.S. Battisti, 1997: ENSO-like interdecadal variability: 1900-93. J. Climate, 10, 1004-1020.

Oceanic Niño Index (ONI) is provided by the NOAA, National Weather Service, National Centers for Environmental Prediction, Camp Springs MA. It is defined as the monthly anomaly in surface ocean temperature between 5° South and 5° North, and between 120° West and 170° West. ONI is the official El Niño and La Niña indicator.
http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

Aleutian Low Pressure Index (ALPI) measures the relative intensity of the Aleutian Low pressure system of the North Pacific (December through March). It is calculated as the mean area (km^2) with sea level pressure greater than or equal to 100.5 kPa and expressed as an anomaly from the 1950-1997 mean..The value for 2009 is based on air pressure from Dec. 2008 to March 2009. A positive index value reflects a relatively strong, or intense Aleutian Low http://www.pac.dfo-mpo.gc.ca/science/species-especes/climatology-ie/cori-irco/alpi/index-eng.htm

North Pacific Gyre Oscillation (NPGO) is a pattern of sea surface height variability of the northeast Pacific Ocean. It is distinct from the Pacific Decadal Oscillation, and in general is strongest and most positive when the winter Aleutian Low is very intense (low pressure) and confined to the northern Gulf of Alaska, as occurred in late 1990s to early 21st century. http://www.o3d.org/npgo/

NORTHEAST PACIFIC SEA LEVEL INDEX (NPSL)

Patrick Cummins, Fisheries and Oceans Canada

An index of variability over the northeast Pacific Ocean is constructed based on sea level anomalies measured by satellite altimetry. The index, denoted the Northeast Pacific Sea Level (NPSL) index, is a time series calculated by regressing observed anomalies onto the leading empirical orthogonal function of sea level over the region. The spatial pattern of this mode is not shown here, but it may be found in the previous report in this series (Cummins, 2009). The region represented by the index encompasses the entire eastern side of the North Pacific, and is bound to the south by the 30°N latitude circle and to the west by the 180°W meridian. On interannual time scales, sea level anomalies are thought to reflect changes in the height of the water column associated principally with integrated temperature anomalies through the top few hundred meters of the water column. The index then is indicative of large-scale, low frequency variability of upper ocean heat content over the region.

Figure 1 presents the NPSL index for the 17-year period from January 1993 through February 2010. The figure also includes the recent history of the Pacific Decadal Oscillation (PDO), a complementary index based on sea surface temperature over the entire extra-tropical North Pacific Ocean. While the two indices show similar variations, the PDO is clearly subject to pronounced variability on relatively short time scales. Due to its greater 'inertia', the sea level index may provide a better indication of long-period upper ocean variability.

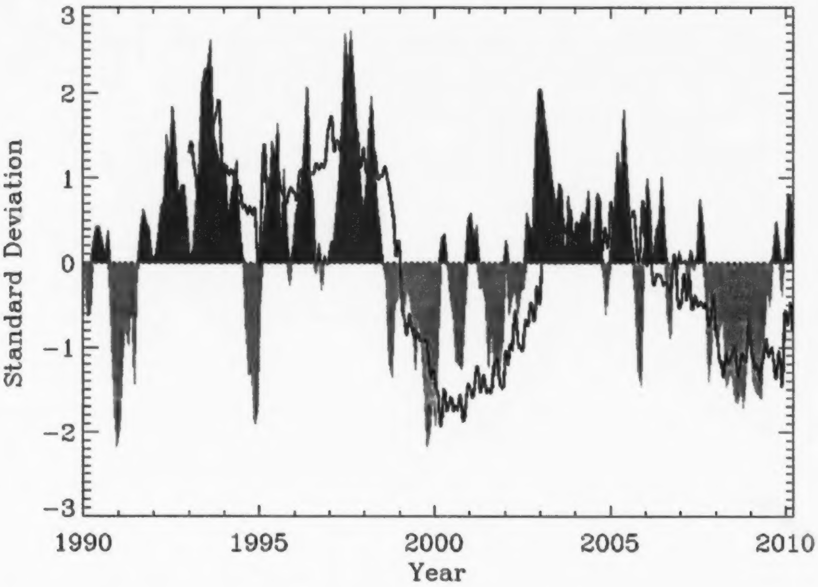


Figure 1. Monthly values of the NE Pacific Sea level Index (NPSL) are indicated by the solid black curve, with positive values for positive sea level anomalies over the Gulf of Alaska and the eastern North Pacific Ocean, and negative values when the NPSL index is negative. Monthly values of the PDO index since 1990 are shown with blue indicating the cold phase of the index, red indicating the warm phase. The two indices have been normalized by their standard deviations. No smoothing has been applied to the monthly values.

Since the end of 2005 and through early 2010, the NPSL has been consistently negative. This is associated with lower sea level and reduced upper-ocean heat content in the Gulf of Alaska and over the northeast Pacific, distributed in a broad horseshoe -shaped pattern. Over this period the PDO also has been generally negative, but with less consistency than the sea level index. During the second half of 2009, the sea level index weakened somewhat, while a shift was seen to positive values of the PDO. This is a consequence, almost certainly, of the El Niño episode that unfolded in the tropical Pacific during the second half of 2009 and continued into 2010.

Presently the outlook for 2010 calls for a weakening of El Niño conditions with the tropical Pacific returning to neutral conditions by the northern hemisphere summer (See Internet site listed below). In addition, there is a growing possibility that La Niña conditions will develop during the fall of 2010. Such an event might lead to the NPSL remaining negative through 2010, continuing the trend seen over the last four years. This outlook implies a return to relatively cool ocean conditions in the northeast Pacific, after the present El Niño episode subsides.

Reference

Cummins, P.F., 2009. Northeast Pacific Sea Level Index, pages 29-30 in: Crawford, W.R. and Irvine, J.R. 2009. *State of physical, biological and selected fishery resources of Pacific Canadian marine ecosystems*. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi+121 p.

El Niño Internet Site, April 2010:

http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_apr2010/ensodisc.pdf

CONDITIONS ALONG LINE P IN 2009 AND EARLY 2010

Marie Robert, Fisheries and Oceans Canada

Line P is a series of oceanographic stations extending from the southwest coast of Vancouver Island to Ocean Station Papa at 50°N 145°W, in the Pacific Ocean. (Fig. 1). The Line P time series is one of the longest of its kind in the world, with data going back to 1956. Fisheries and Oceans Canada visit Line P three times per year, usually in February, June, and August. Sampling is most intense at numbered stations in Figure 1.

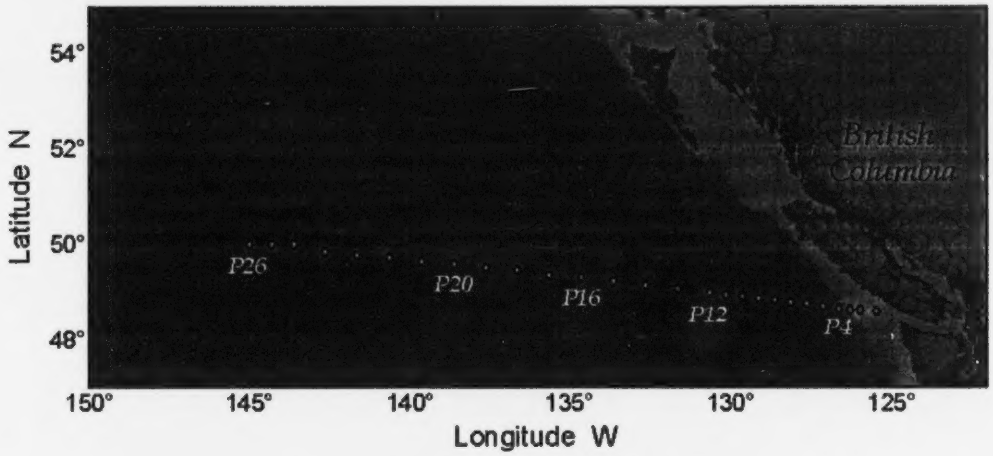


Figure 1. Line P and Ocean Station Papa (P26).

2008 was a very cold year along Line P. In contrast, the waters of the northeast Pacific were noticeably warmer in 2009. Figure 2A shows the difference in temperature between June 2008 and June 2009 along Line P. The water was up to 5°C warmer in some places near the ocean surface. Figure 2B shows the anomaly of temperature in June 2009 with respect to the long-term average (1956 – 1991). Cold waters from 2008 can be seen below the surface.

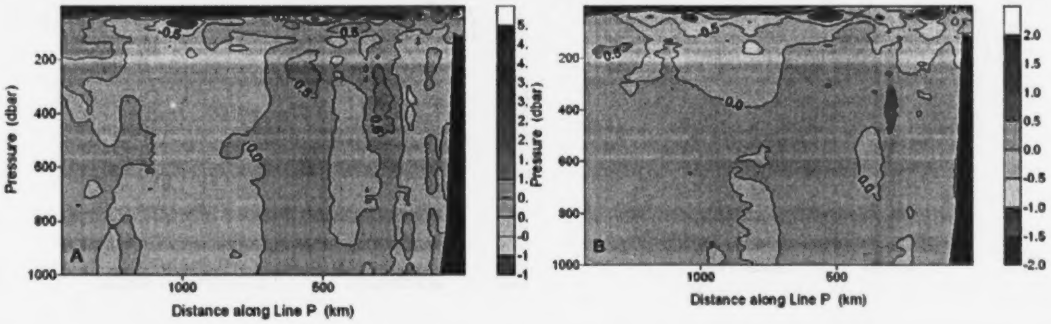


Figure 2: A. Difference in temperature (°C) between June 2009 and June 2008. B. Anomaly of temperature (°C) in June 2009 with respect to the 1956-1991 average. Ocean Station Papa is on the left.

In August 2009 the scenario was the same, although the surface coastal waters were colder than during the previous year, as shown in Figure 3A. Figure 3B shows the temperature anomaly field with respect to the 1956 - 1991 average.

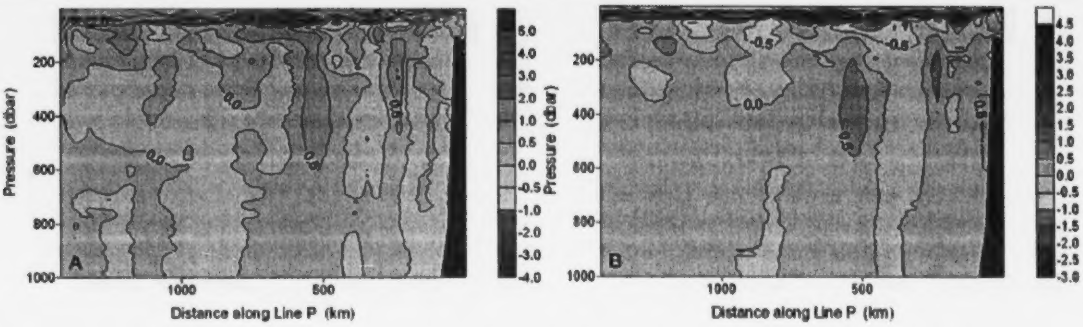


Figure 3: A. Difference in temperature (°C) between August 2009 and August 2008. B. Anomaly of temperature (°C) in August 2009 with respect to the 1956-1991 average. Ocean Station Papa is at left.

If 2009 was much warmer than the previous year, 2010 started even warmer. Figure 4A shows the large temperature anomaly in the coastal waters in February 2010 compared to February 2009, whereas Figure 4B shows the actual temperature contours in February 2010.

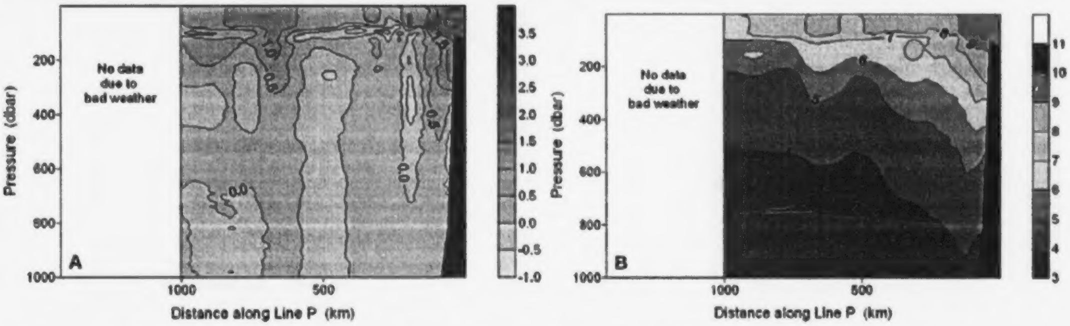


Figure 4: A. Difference in temperature (°C) between February 2010 and February 2009. B. Temperature Field (°C) in February 2010. Ocean Station Papa is at left.

Regarding salinity, 2009 seemed slightly fresher than 2008, although the difference is less striking than in temperature, as seen in Figure 5A for June and 5B for August.

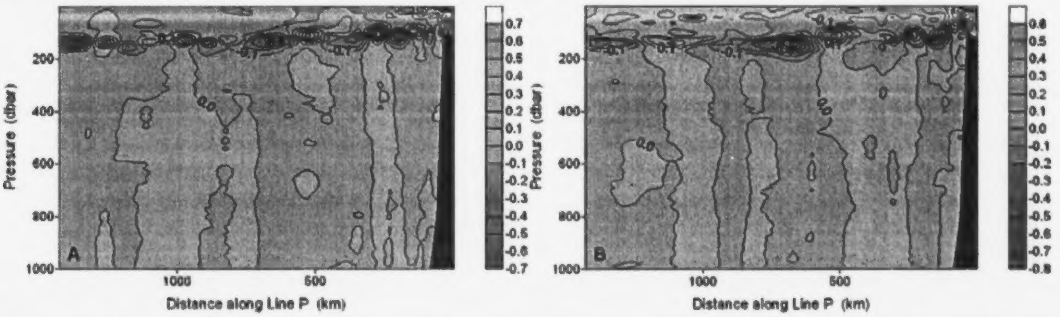


Figure 5: A. Difference in salinity between June 2009 and June 2008. B. Difference in salinity between August 2009 and August 2008. Ocean Station Papa is at left.

UNREMARKABLE NUTRIENT AND OXYGEN DYNAMICS IN SUBARCTIC PACIFIC IN 2009

Frank Whitney, Fisheries and Oceans Canada

Oxygen

Previous reports on the state of the northeast Pacific Ocean (Whitney 2009), showed how hypoxia (very low oxygen concentration) is spreading slowly along the BC coast, and possibly stressing near-bottom marine life between ~150 and 500 m depth. Although not a greater problem in 2009, this trend will likely persist due to large-scale ongoing changes in the ocean (winter warming in northeast Asia, apparent reductions in Okhotsk Sea ice cover, a freshening trend in waters of the subarctic Pacific), although the 18.6-year lunar nodal cycle appears to influence tidal mixing in straits between the Kurile and Aleutian Islands. This cycle is likely responsible for oscillations seen in time series oxygen data from the Oyashio (Oy) and Eastern Subarctic Pacific (ESP) regions (see Fig. 1 for locations). The PICES report entitled The North Pacific Ocean, 2003-2008 (McKinnell et al., in review) provides details of these trends and oscillations.

Nutrients

DFO ship-of-opportunity and DFO Line P data was used to look for anomalies in nutrient supply to the surface layer across the subarctic Pacific. After iron, nitrate is the most common limiting nutrient for phytoplankton in this region. Silicate utilization is also important since it supports growth of diatoms that form an important phytoplankton group responsible for most carbon export to higher trophic levels. The SERIES iron enrichment study of 2002 showed that, due to the faster recycling of nitrogen, silicate can limit diatom growth in the eastern Subarctic Pacific (ESP) (e.g. Whitney et al., 2005). The preferential removal of silicate over nitrate (and phosphate) from the upper ocean is termed the silicate pump. Despite efficient removal from the upper ocean, silicate levels remain high in the subarctic Pacific due mainly to large riverine inputs.

Winter nitrate concentrations correlate well with nutrient levels found below the mixed layer. Distributions of nutrients at 100 m, as shown in plots found on various web sites (e.g. World Ocean Data Base or World Ocean Circulation Experiment), look very similar to winter levels in the bottom panel of Fig. 1. An exception to this trend is found in subtropical waters (e.g CSTP in Fig. 1) where light levels are high enough for phytoplankton to use surface nitrate at all times of year, thus eliminating any winter accumulation.

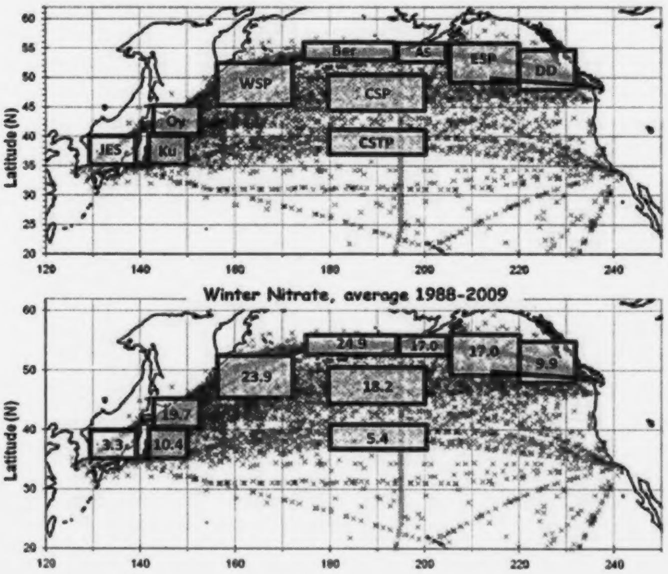


Figure 1. Average nitrate concentrations in winter based on ship of opportunity and research cruise data collected from 1988 to 2009. Red crosses denote sampling locations and boxes label the domains (upper panel) in which winter averages (lower panel) were computed. Line P is shown as a dark blue line.

The southern Bering Sea (Ber) and Western Subarctic Pacific

(WSP), followed by the Oyashio region (Oy), have the highest winter levels of nitrate and silicate. Nutrients are more effectively used in the Oyashio, making this the region with highest nutrient drawdown (~18 µM nitrate and 30 µM silicate). Weaker nutrient supply and stronger iron limitation throughout the Central (CSP) and Eastern Subarctic (ESP) result in an annual nitrate drawdown of ~8 µM and a residual summer nitrate concentration of ~9 µM.

Interannual variability in nutrient levels is best seen from repeat surveys along Line P. (This line of sampling stations is located along the dark blue line in the southern part of DD and ESP boxes in Fig. 1.) The supply and seasonal drawdown of nitrate and silicate has fluctuated considerably over the past 2 decades. Winter levels (Fig. 2) of both were high in 1988-1990, as they were in the 1970s (Whitney et al., 1999) but declined strongly through the warm mid-1990s as a series of El Niño events transported heat and subtropical waters northward. Nutrient levels recovered following the 1999 La Niña, peaking in the cold 2002 and 2008 winters.

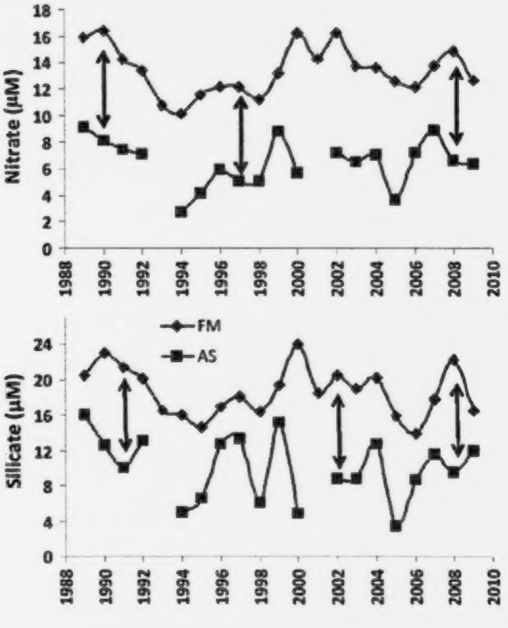


Figure 2. Surface nutrients in winter (Feb and Mar, blue) and summer (Aug and Sep, red) in the ESP part of Line P (the high-nutrient, low-chlorophyll region). Arrows provide a scale for seasonal drawdown of 6 µM nitrate and 8 µM silicate. Occasionally, the outer end of Line P did not get sampled for a variety of reasons.

A phytoplankton bloom across most of the subarctic Pacific in August 2008 resulted in a strong removal of nutrients from the surface layer (Hamme et al., in prep.) In the 2009 winter following this rare event, nutrients did not recover to levels of the previous winter.

One might speculate that the weak supply and drawdown of silicate in 2009 was a carryover of the impact of the abnormal bloom observed in 2008. Throughout this time series, there is less interannual variability in the seasonal drawdown of nitrate (6.8 +/- 2.3 µM) than silicate (7.8+/- 5.1 µM), suggesting diatom production fluctuates more than total community primary production.

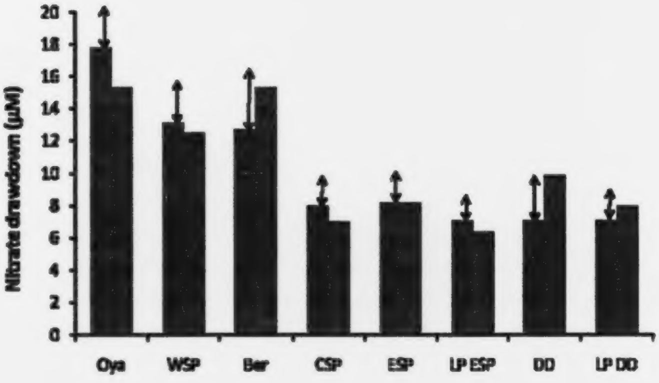


Figure 3. The average seasonal removal of nitrate from various domains in the subarctic Pacific between 1988 and 2008 (red bars, arrows denote the standard deviation) and in 2009 (blue bars). Line P (LP) estimates are provided in the two eastern domains (ESP and DD).

In 2009, nitrate drawdown was near average in the ESP and somewhat above average in the Dilute Domain (DD) off the west coast of Vancouver Island (Fig. 3). Other regions of the subarctic likewise were close to historical averages. However silicate drawdown (Fig. 2) was only 4.2 µM in the ESP part of Line P, well below the average of 11 µM in the 1970s and 7 µM in the 1990s (Whitney et al., 1999). Line P data from 1988 to 2009 show a slight declining trend in silicate supply to the surface layer. Between 100 and 400 m, silicate and nitrate levels are steadily increasing over the past 2 decades (data not shown). Storage of nutrient in the ocean interior must be affecting nutrient supply to the upper ocean throughout the subarctic, although sufficient data are not available to identify which regions are being most strongly impacted.

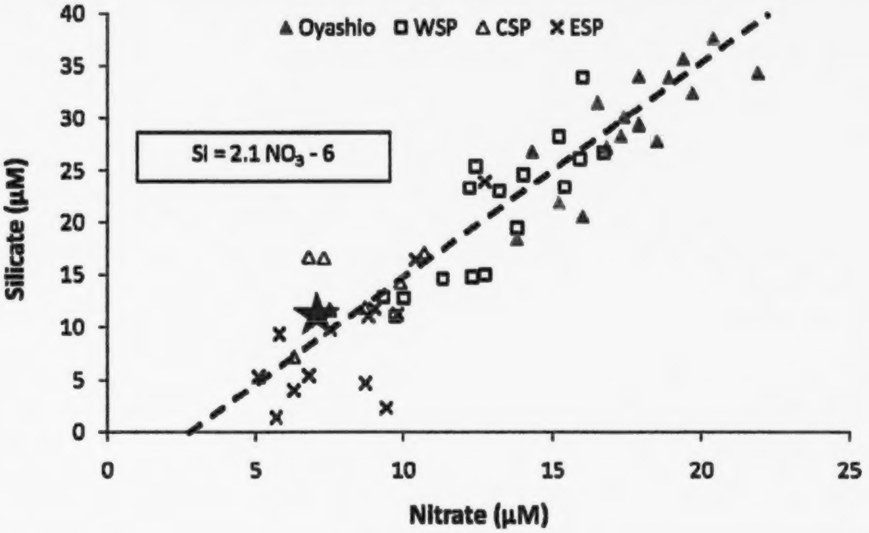


Figure 4. Silicate versus nitrate drawdown in surface waters of subarctic domains of the North Pacific between 1988 and 2008. The blue star is the average for Station P (50 N, 145 W) from data in Fig. 2. The dashed line and equation in the box show the linear regression of these data.

Some general conclusions on nutrient utilization by phytoplankton can be inferred from drawdown rates observed in subarctic domains. Drawdown is the observed seasonal removal of nutrients from seawater, an estimate that involves uncertainties due to advection and remineralization, and should not be confused with uptake by phytoplankton. Nutrients are seasonally removed from seawater at a rate of 2.1 µM silicate per µM nitrate (Fig. 4), except that the first few micromoles of nitrate are not accompanied by silicate drawdown. By comparison, Brzezinski (2003) has estimated the silicate/nitrate requirement ratio of diatoms to be ~1.0. In regions of low nutrient drawdown such as the Eastern and Central Subarctic Pacific, diatoms are a low fraction of the phytoplankton biomass most years. Since diatoms are considered the most effective phytoplankton group in transferring energy to higher trophic levels, areas with higher silicate drawdown such as the Oyashio will better support fish production.

The highest productivity regions of the N Pacific are its coastal waters, where fish production is greatest. However, it is difficult to assess productivity of these areas from nutrient dynamics due to infrequent sampling. Tides, upwelling and wind bursts commonly enhance nutrient supply far beyond what is accumulated during winter. Assessing the productivity of the open subarctic ocean based on nutrients helps us understand interannual variability that affects the health of resident zooplankton and small fishes, as well as the migratory fishes, squid and seabirds that enter these domains to feed.

References

Brzezinski, M.A., Dickson, M., Nelson, D.M., Sambrotto, R., 2003. Ratios of Si, C and N uptake by microplankton in the Southern Ocean. *Deep-Sea Res. II* 50, 619–633.

Hamme, Roberta C., Peter W. Webley, William R. Crawford, Frank A. Whitney, Michael DeGrandpre, Steven Emerson, Charles Eriksen, Karina Giesbrecht, Jim Gower, Maria Kavanaugh, Angelica Peña, Christopher Sabine, Laurence Coogan, Sonia Batten, Deirdre Lockwood & Damian Grundle. in prep. Volcanic ash fuels anomalous plankton bloom in subarctic Northeast Pacific.

McKinnell, S., S. Batten, S. Bograd, J. Boldt, N. Bond, S. Chiba, M. Dagg, M. Foreman, G. Hunt, J. R. Irvine, O. Katugin, D.L. Mackas, V. Lobanov, P. Mundy, V. Radchenko, Young Jae Ro, H. Sugisaki, F. Whitney, A. Yatsu, and S. Yoo. In review. The North Pacific Ocean, 2003-2008. *PICES Press.*

Whitney, Frank, 2009. Spreading hypoxia in deep waters along the west coast. Page 55 of *State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems.* DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi + 121 p, edited by Crawford, W.R. and J. R. Irvine. http://www.dfo-mpo.gc.ca/CSAS/Csas/Publications/ResDocs-DocRech/2009/2009_022_e.htm

Whitney, F.A., Freeland, H.J., 1999. Variability in upper-ocean water properties in the NE Pacific Ocean. *Deep-Sea Res.* II 46, 2351–2370.

Whitney, F.A., Crawford, D.W., Yoshimura, T. 2005. The uptake and export of Si and N in HNLC waters of the NE Pacific. *Deep-Sea Res. II,* 52, 1055-1067.

AN ARGO VIEW OF THE GULF OF ALASKA

Howard Freeland, Fisheries and Oceans Canada

The International Argo program provides measurements from more than 3000 free-floating "robots" in global oceans, measuring temperature and salinity in the top 2000 metres every 10 days. Canada places Argo "robots" off both its Pacific and Atlantic coasts to monitor changes in ocean properties for seasonal weather prediction, climate studies and fisheries applications.

Argo "robots" (normally called "floats") supply real-time temperature and salinity observations of the ocean, and dissolved oxygen profiles are also available for a few of the floats. The number of floats supplying profiles at 10-day intervals is sufficient to allow interpolation of properties onto Ocean Station Papa at 50°N, 145°W, and a map of the anomaly of water density (specifically σ_t) versus time and depth is shown in Figure 1.

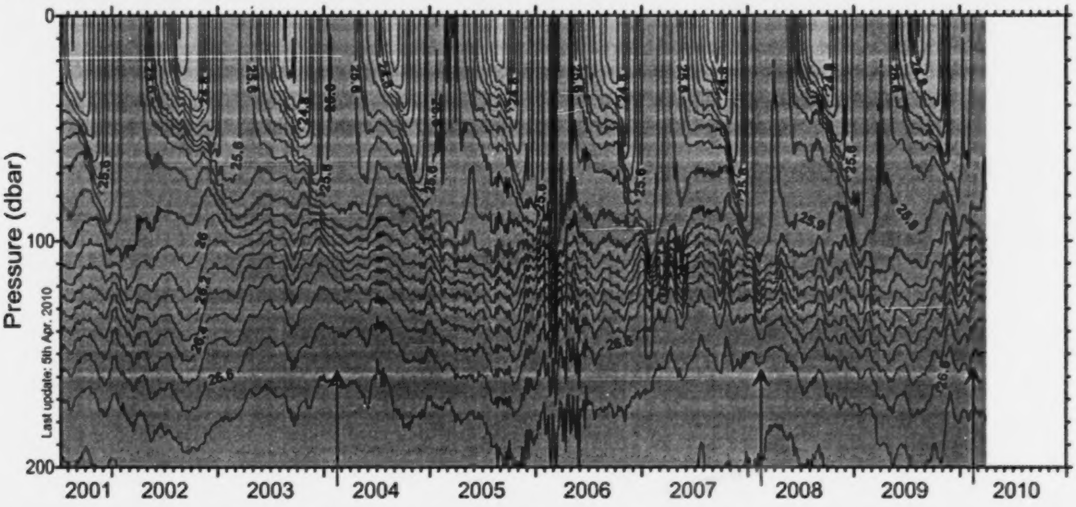


Figure 1. Density anomaly at Ocean Station Papa, with years along the x-axis and depth below surface on y-axis. The green contour marks 25.8 kg/m^3 and the red line 25.9 kg/m^3. The three arrows mark the months of the maps of mixed-layer depth shown in Figure 2. The contour interval is 0.1 for densities greater than 25.6 kg/m^3 and 0.2 less than 25.6 kg/m^3.

Focusing on the green line we see that in some winters, such as 2001/02 and recent winters, mixing has been strong enough to bring that contour to the surface. During the four winters starting in 2002/03 the Gulf of Alaska was in a period of unusually strong stratification that prevented deep mixing. The green contour reached the surface again in the winter of 2006/7, and in the unusual winter of 2007/08 mixing brought the next density surface (25.9 kg/m^3) almost to the sea surface. As a result, this was a period of weak stratification. During 2009 stratification returned to normal and as of mid-March 2010 not even the rather light density surface of 25.7 kg/m^3 has reached the surface, revealing strong stratification.

Marine life in the Gulf of Alaska relies on winter mixing to bring nutrients to the surface. Weaker winds in other seasons cannot supply these nutrients. Between spring and autumn there is sufficient light to support growth of phytoplankton and other microbial plants near the ocean surface. This annual cycle of winter mixing and spring-to-autumn growth supports the marine food web. Winters of strong stratification impede this nutrient supply. We measure the stratification and depth of the upper wind-mixed layer each winter as indicators of this nutrient supply.

The typical February distribution of mixed-layer depths in the Gulf of Alaska (Figure 2a) is computed as an average over 2002 to 2010, the years of complete Argo data. Figures 2b, 2c and 2d reveal the differences from average depths in the months corresponding to the three arrows marked in Figure 1.

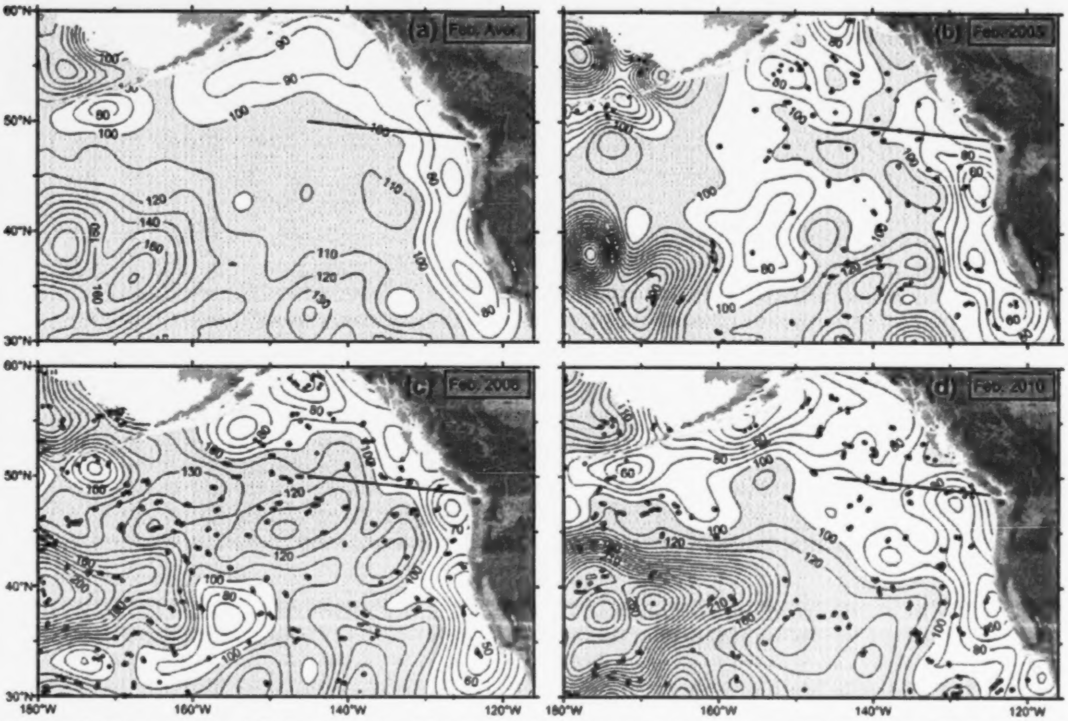


Figure 2. Four maps of February mixed-layer depth distribution in the northeast Pacific. Panel a shows the average over the entire Argo period of 2002 to 2010. Panels 2b-d show mixed-layer depth anomalies for three individual February months in 2005, 2008 and 2010. The shaded regions indicate mixed-layer depths greater than normal. Argo observation sites are indicated by the red dots. Line P is the blue line.

The shading on the maps indicates areas with positive anomaly (mixed-layer depths greater than normal) and we clearly see the link between the strong stratification at Station Papa in February 2004 (Fig. 1) and the shallow mixed layer over most of the Gulf of Alaska in this month (Fig. 2b). There is also a link between the weak stratification in February 2008 and the deep mixed layer in Fig. 2c. As we move through the winter of 2009/10 we appear to be in another period of somewhat higher-than-normal stratification and consequently shallow mixed layer. In many respects the physical conditions in February 2010 resemble those of February 2004.

The 2009/10 El Niño began in late summer 2009 and continues well into 2010. (El Niño officially occurs when ocean temperatures remain well above normal in the equatorial Pacific for at least five consecutive months.) In normal winters El Niño also brings increased temperatures to the continental shelf from California to northern British Columbia; the present El Niño brought these higher temperatures by January 2010.

Our longest ship-based sampling time series off the west coast is along Line-P, but we have only three cruises per year. We can interpolate between Argo observations to reproduce a Line-P survey of temperature and salinity. These are very low resolution surveys and miss the continental shelf, but they do sample in every month. Of course, Argo floats do not sample to the ocean bottom and do not carry the suite of biological and chemical measurements that normally accompany a Line-P survey.

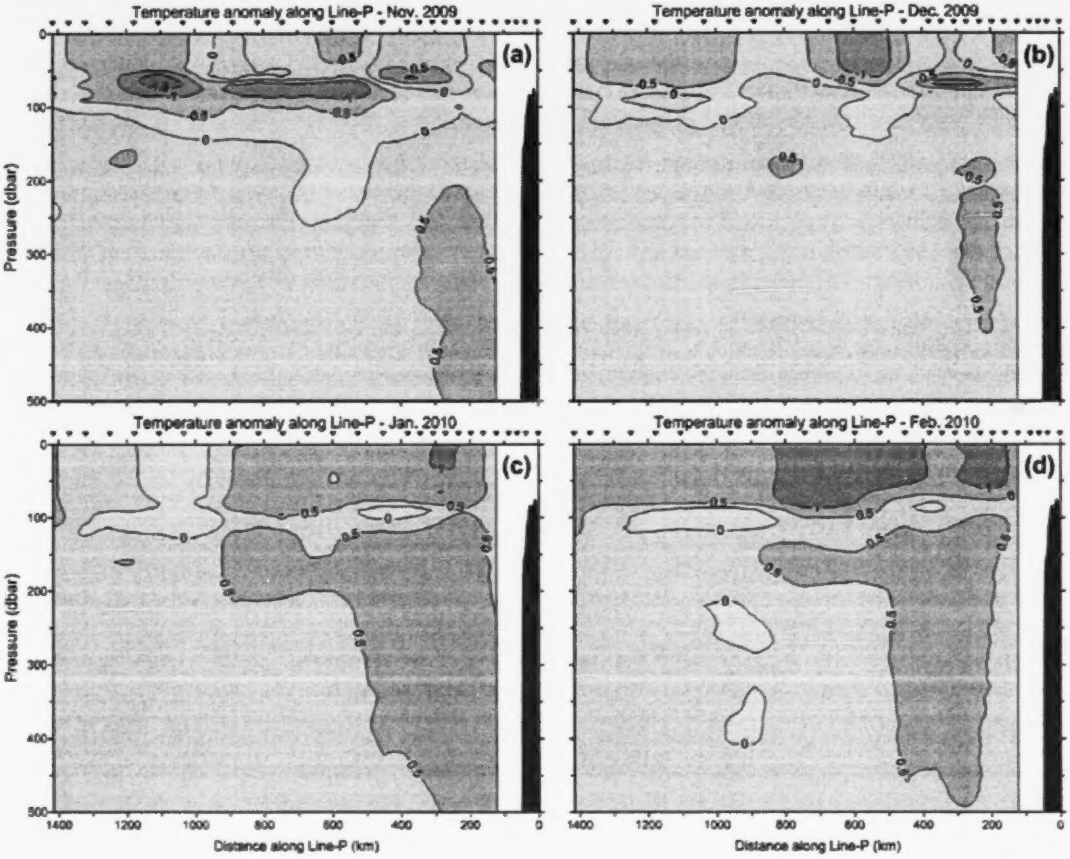


Figure 3. The panels (a) to (d) show the evolution of temperature anomaly through the winter of 2009/10 along Line-P, interpolated from the Argo array. The continental shelf of Canada is at right of each panel. Red regions denote temperatures above average, blue are below average.

The panels in Figure 3 clearly show the ubiquitous cool water that dominated the near surface regions of the Gulf of Alaska through much of 2009 finally yielding to warming in early 2010. The warming is likely related to El Niño. Argo will continue to monitor these waters monthly.

A technique was developed that allowed Argo observations to be fitted to a numerical model of the northeast Pacific and this allows us to use the combination of data and modelling to monitor the changing circulation of the northeast Pacific. These results suggest that the circulation patterns are going through an unusual phase right now.

Figure 4 shows the distribution of dynamic height in the northeast Pacific computed by fitting Argo observations of ocean density to an ocean model. Dynamic height is a variable computed from seawater density that has a role similar to that of pressure in the atmosphere. Flow is along lines of constant dynamic height, and is faster when contours are close together.

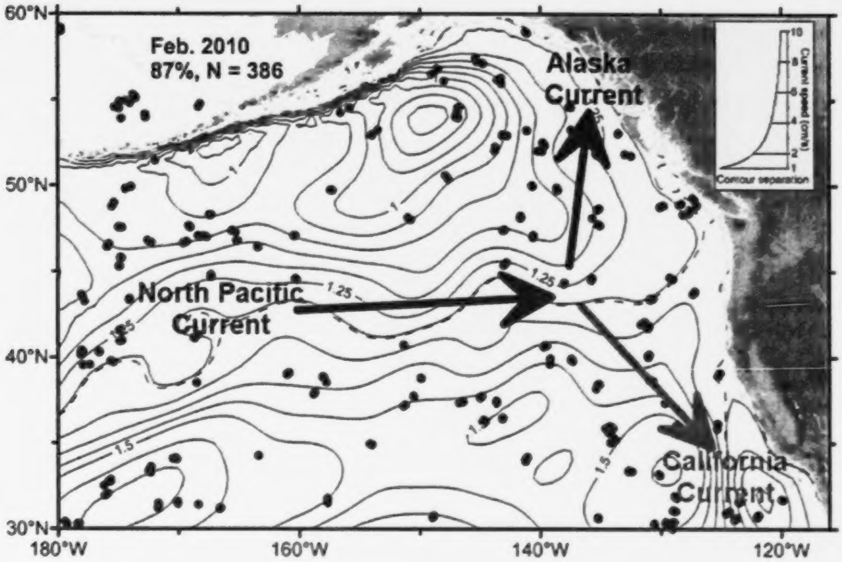


Figure 4. The black contours show the distribution of dynamic height in the N.E. Pacific for February 2010, the red dots indicate where Argo observations were acquired. Ocean currents generally flow along these contours

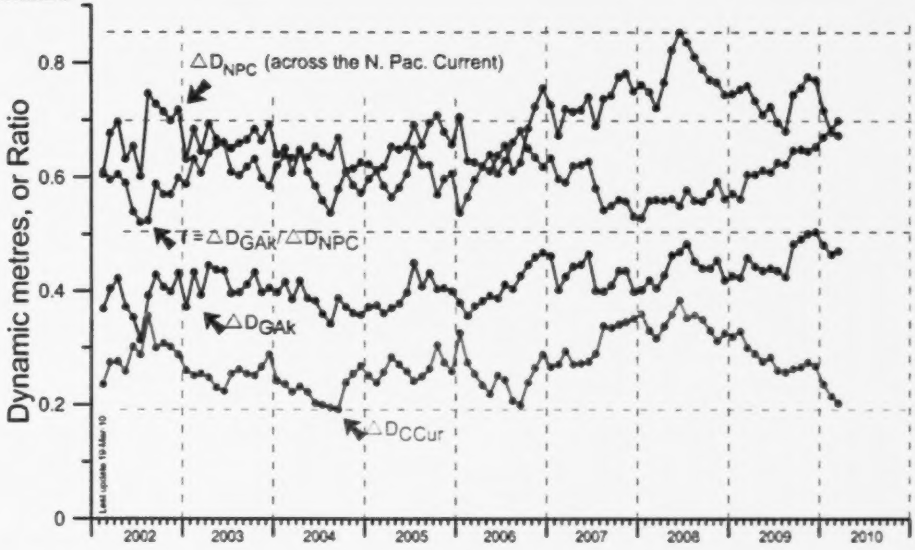


Figure 5. The black, blue and green lines indicate the strength of flow in the three currents marked in Figure 4. The red line is the ratio of the blue line divided by the black line and so represents the fraction of the North Pacific Current that flows northward into the Gulf of Alaska.

The black arrow in Figure 4 locates the main North Pacific Current that is an extension of the Kuroshio Current heading toward the west coast of North America. This current splits into two branches when it nears the west coast; part of the water flows into the Alaska Current (the blue arrow) and parts flows into the California Current (the green arrow). The dashed contour is the "dividing contour", if this current pattern remains steady, then any water to the north of the dashed line will eventually head into the Alaska Current and anything to the south heads into the California Current. The differences in dynamic height across one of the currents indicates the strength of the flow in that current and these are plotted in Figure 5.

Figure 5 shows that in the time that Argo observations have provided information to monitor the currents in the North Pacific (2002 to present) we saw the largest flow of water into the Gulf of Alaska (blue line) in December 2009. Meanwhile the flow of water through the California Current (green line) in early 2010 is near the minimum. The amount of water coming in from the west in the North Pacific Current is not unusual right now. That current gradually increased in strength from 2004 to mid-2008 and then steadily declined. At the end of 2009 and as of early 2010 it is near the long-term average. However, the red line indicates that the fraction of the North Pacific Current that ultimately heads into the Gulf of Alaska is the highest seen so far.

It is not at all obvious what would be the impact of these circulation changes on the biology of the North Pacific, and also it is not obvious why these changes are occurring. It is interesting that the Argo array is showing the largest ever diversion of water northwards at the same time that an El Niño event appears to be developing on the equator, this is a potential linkage that remains to be explored.

REMOTE SENSING OF CHLOROPHYLL IN GULF OF ALASKA

Jim Gower and Stephanie King, Fisheries and Oceans Canada

We use time series of data from SeaWiFS and MODIS satellite ocean colour imagers to monitor plankton productivity and blooms in the Gulf of Alaska and along the BC coast. These satellites can determine the chlorophyll concentration at the ocean surface based on the colour of the water. Chlorophyll in turn indicates the present of phytoplankton, the microscopic marine plants that drift in the surface waters of the ocean and coastal seas.

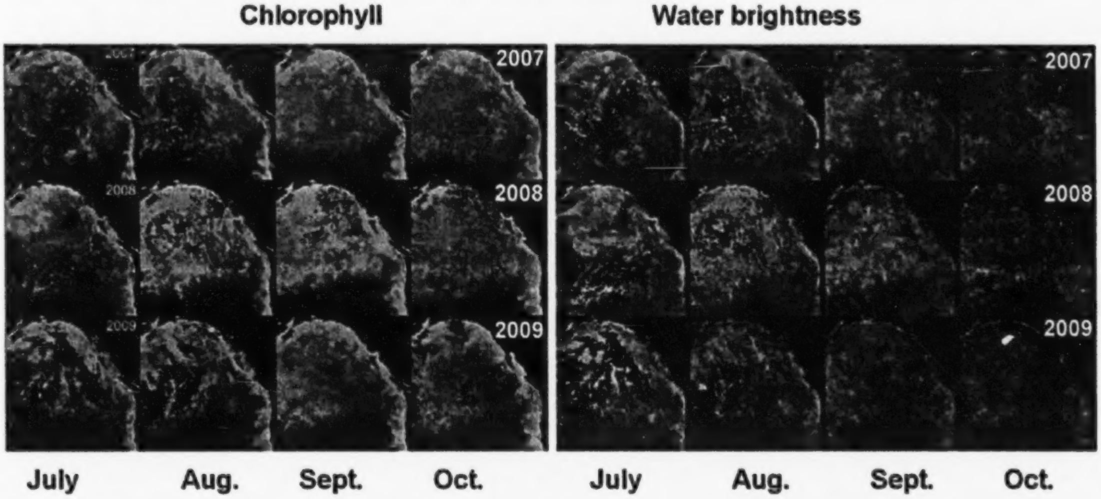


Figure 1. Monthly data composites of the Gulf of Alaska for July to October (left to right) in 2007 (top) to 2009 (bottom) for chlorophyll (left) and water brightness (right). Both brightness and chlorophyll increase as colours change from blue to yellows to red. Black regions denote land and also oceanic regions with no chlorophyll data due to cloud cover.

In the summer of 2008, these images showed a large-area bloom that was detected as a significant increase in both derived chlorophyll concentration and water brightness. The bloom is postulated to be due to iron input from the Aleutian volcano Kasatochi, which erupted on August 7 2008. Winds carried ash from this volcano was carried all across the Gulf of Alaska. Figure 1 shows the higher chlorophyll concentrations and water brightness in August and September 2008 compared to other months. Chlorophyll returned to near-average concentrations in the summer of 2009.

MESOZOOPLANKTON IN THE GULF OF ALASKA IN 2009: IN TRANSITION?

Sonia Batten, Sir Alister Hardy Foundation for Ocean Science, UK

Recent ocean observations suggest that El Niño effects were evident in our region late in 2009 and early 2010 as warm water moved north. Mesozooplankton in spring and summer 2009 were, however, still influenced by the remnants of the cool conditions of the previous winter, making 2009 somewhat of a transition year between cold and warm.

In 2009 the seasonal cycle of total mesozooplankton biomass measured by Continuous Plankton Recorder (for the area outlined in Figure 1) followed the average pattern of 2000-08, as shown in Figure 2. In contrast, during the very cold year of 2008 the spring peak was delayed until June and reduced in mass, and highest biomass was actually seen in late summer.

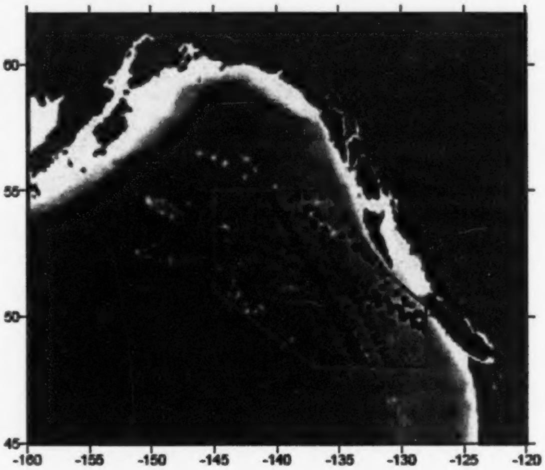


Figure 1. Region of sampling by Continuous Plankton Recorder (CPR). Red lines enclose waters sampled for this report. Black dots indicate sample positions.

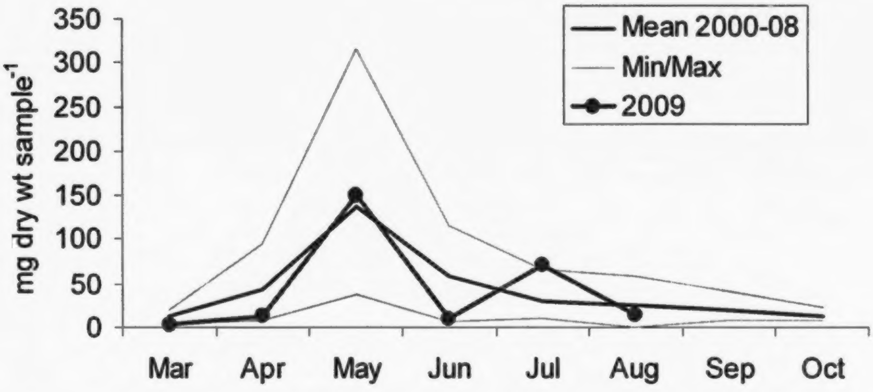


Figure 2. Mean monthly biomass for 2009, together with monthly mean, minimum and maximum mesozooplankton biomass (2000-08) in mg dry weight per sample (~3m^3) from CPR sampling (which occurs approx. monthly 6-9 times p.a. between March and October) in the off-shore Gulf of Alaska area. Data for July and August 2009 are preliminary.

Timing of the spring biomass peak in 2009 (Figure 3) for the dominant spring copepod, *Neocalanus plumchrus/flemingeri*, was close to the average of the 10-year record, and the time of peak biomass was much earlier than observed in 2008 when ocean temperatures were much cooler. These copepods live at the ocean surface for only a month or two near time of maximum size and abundance. Changes in timing of its growth will determine in which months it is available as food for predators that take advantage of this prey's peak abundance.

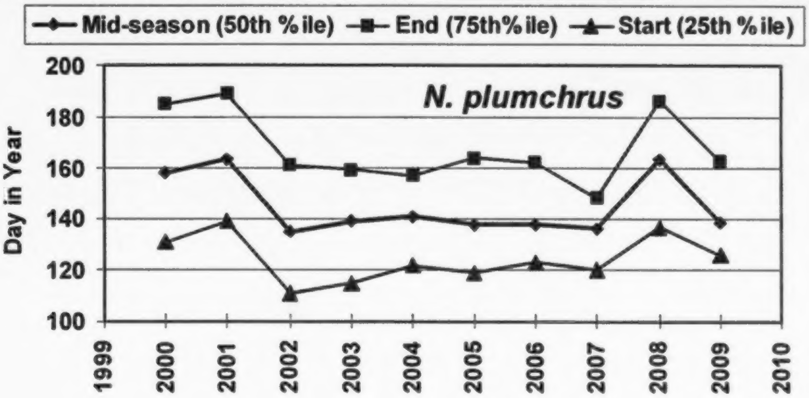


Figure 3. Day of year at which 25th, 50th and 75th percentile of cumulative biomass of Neocalanus plumchrus/flemingeri *was reached for the offshore Gulf of Alaska region.*

Community composition analyses of summer samples (though data for summer 2009 are provisional at this time) show a clear relationship between temperature and community composition (Fig 4).The non-metric Multidimensional Scaling Analysis of log-transformed abundance data for individual mesozooplankton taxa (62 taxa) shows a clear gradient, with the warmest years at the top of the plot and coldest years at the bottom (Figure 4). Transition years (2003 transitioning from cold to warm, 2006 transitioning from warm to cold and tentatively 2009 cold to warm again) plot in the centre. 1997 stands out as an unusual year; it was the start of a strong El Niño. 2007 also stands out at the other extreme, although there is no explanation of this anomaly as yet. The y-dimension (vertical axis) is significantly ($p<0.01$) positively correlated with the summer temperature as measured at Amphitrite Point lighthouse (mean of June, July and August). The x-axis is significantly correlated with the PDO index, ($p<0.05$) however this is mostly driven by the El Niño year of 1997 plotting far to the right. Composition of the plankton and the taxa that are present may influence the nutritional value of the zooplankton to predators. Given that the El Niño is affecting BC waters early in 2010, we expect community composition in 2010 to plot towards the upper right of the nMDS plot

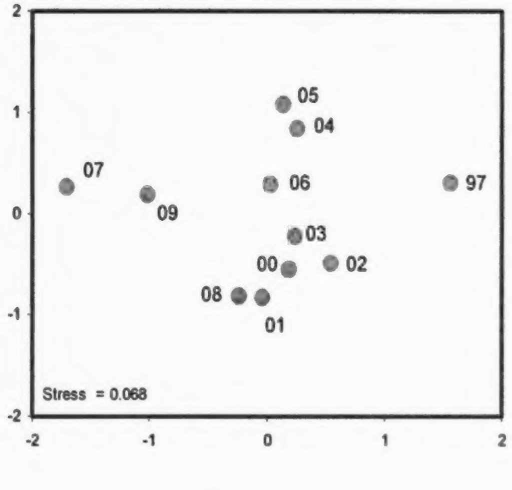


Figure 4. nMDS plot of mean summer (28 June to 31st August) community composition. Years that plot closest together are most similar. Data were log-transformed first to reduce the effects of dominant taxa.

http://pices.int/projects/tcprsotnp/default.aspx for data and more information

ALASKA'S "ECOSYSTEM CONSIDERATIONS FOR 2010" REPORT

Jennifer Boldt[1*], Kerim Aydin[2], Sonia Batten[3], Nick Bond[1], Sherri Dressel[4], Lowell Fritz[5], Sarah Gaichas[2], Kyle Hebert[4], Terry Hiatt[2], Carol Ladd[6], Michael Martin[2], Franz Mueter[7], John Olson[2], Jim Overland[6], Chris Rooper[2], Dan Urban[2], Carrie Worton[4], Stephani Zador[1].

[1]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington
[2]National Marine Fisheries Service [3]Sir Alister Hardy Foundation for Ocean Science
[4]Alaska Department of Fish and Game [5]National Marine Mammal Laboratory
[6]Pacific Marine Environmental Laboratory
[7]University of Alaska Fairbanks, School of Fisheries and Ocean Sciences
*Currently with Fisheries and Oceans Canada

In Alaska, ecosystem pressure and state indicators are assessed annually and summarized in the Ecosystem Considerations report (http://access.afsc.noaa.gov/reem/ecoweb/index.cfm). The main intent of this report is to update, summarize, and synthesize historical climate and fishing effects on the shelf and slope regions of the eastern Bering Sea/Aleutian Islands and Gulf of Alaska from an ecosystem perspective and to assess possible future effects of climate and fishing on ecosystem structure and function. Recent information specific to the Gulf of Alaska (GOA; Figure 1) is summarized here for DFO's "State of the Ocean" report.

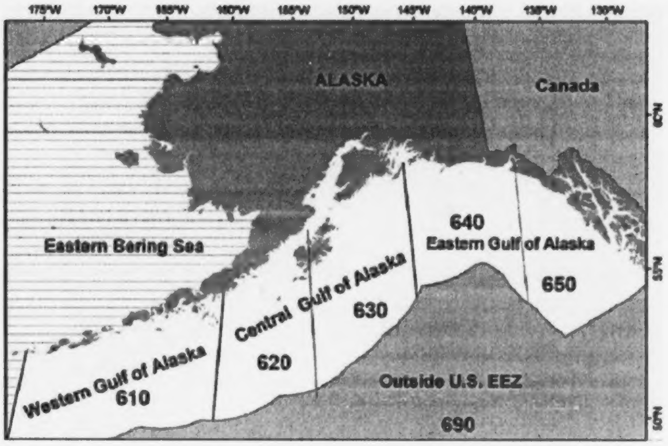


Figure 1. North Pacific Fisheries Management Council groundfish fishery management areas in the Exclusive Economic Zone of the United States in the Gulf of Alaska.

Climate and Physical Environment Trends

- The North Pacific atmosphere-ocean system from fall 2008 through summer 2009 featured relatively cool sea surface temperatures (SST) along its northeastern flank, extending from the Bering Sea to the south coast of Alaska (GOA), southeast Alaska and the west coast of British Columbia to California (Bond and Overland 2009).
- Consequences of a weak Aleutian low during the past winter and spring 2009 included mostly upwelling-favorable wind anomalies on the continental shelf from the GOA to the Pacific Northwest (Bond and Overland 2009).
- The 2008/09 winter included a La Niña of modest amplitude; the higher latitude response to the tropical Pacific was stronger than during the previous winter, even though the 2007/08 La Niña was stronger (Bond and Overland 2009).
- El Niño conditions developed in the summer of 2009 (Bond and Overland 2009).

- In 2007 and 2009, the surface temperatures in the GOA cooled markedly with a temperature inversion at the 100 m depth contour (Martin 2009a).
- The eastern portion of the Alaska Peninsula and Aleutian Islands experienced suppressed storminess during winter and spring 2009; the sense of the wind anomalies since late 2008 (to summer, 2009) was from the east to southeast, which is associated with enhanced transports through Unimak and the other shallow passes in the eastern Aleutian Islands (Bond and Overland 2009).
- In 2009, there was a relatively weak and broad Alaska Current off the coast of SE Alaska, as compared with 2008, accompanied by relatively shallow mixed-layer depths in the winter and spring of 2009 (Bond and Overland 2009).
- Based on the winds along the northern GOA coast, the Alaska Coastal Current on the shelf was probably relatively weak during the winter and spring 2009, returning to near-normal transports in the summer of 2009 (Bond and Overland 2009).
- In the GOA, eddy kinetic energy values in an area southwest of Prince William Sound were low in spring 2009. This implies phytoplankton biomass was likely tightly confined to the shelf, and cross-shelf transport of heat, salt, and nutrients was likely to be smaller than in 2007-2008 (Ladd 2009).

Ecosystem Trends

- Mesozooplankton abundance in the GOA tends to peak later in the year and is longer in duration in cool, PDO-negative years compared to warmer, PDO-positive years when the peak abundance tends to be earlier in the year and of shorter duration. In 2008, a cold year, mesozooplankton biomass peaked one month later and persisted longer (Batten 2009).
- The 2008 and 2005 estimates of herring spawning biomass in Southeast Alaska were the two highest in the 25-year time series. Mature age-3 herring abundance is at low levels, but there has been recruitment to spawning stocks at older ages (Hebert and Dressel 2009).
- Abundance of eulachon in the Central and Eastern GOA management area (the 200-mile U.S. Exclusive Economic Zone of the United States) appears to have increased in recent years, possibly indicating increased availability of eulachon to fish, bird and mammal species (Figure 1; Martin 2009b).
- There is strong indication for above-average groundfish recruitment in the GOA management area from 1994-2000 and below-average recruitment since 2001 (Mueter 2008).
- Annual surplus production, an estimate of the sum of new growth and recruitment minus deaths from natural mortality (i.e. mortality from all non-fishery sources) during a given year, in the GOA management area was lower than that of the eastern Bering Sea, less variable and decreased slightly between 1977 and 2007 (Mueter 2009).
- ADFG/NMFS small mesh nearshore surveys indicate a continued low pink shrimp Catch Per Unit Effort (CPUE) since the 1977 climate regime shift; arrowtooth flounder & Pacific cod dominate catches (Urban 2009).
- Arrowtooth flounder, flathead sole, and other flatfish continued to dominate the catches in the ADFG GOA large-mesh trawl survey. A decrease in overall biomass was apparent in 2007 and 2008 from years of record high catches seen from 2002 to 2005 (Worton 2009).
- The mean-weighted distribution of GOA rockfish (1990-2007), especially juvenile Pacific ocean perch, appeared to be farther north and west and was more contracted in 2007,

possibly indicating a change in rockfish distribution around the GOA management area (Rooper 2008).

- Steller sea lion non-pup counts during 2008 increased in the eastern GOA, declined in the central and western Aleutian Islands, and remained relatively stable in between (Fritz 2007).

Fishing and Fisheries Trends

- No GOA groundfish stock or stock complex is overfished or being subjected to overfishing.
- Discards and discard rates in 2008 increased slightly in the GOA, but remained below those observed prior to 1998 when regulations were implemented prohibiting discards of pollock and cod (Hiatt 2008).
- In 2008, observed hook and line fishing effort was near average in the GOA. Bottom trawl fishing effort in 2008 was near or below the 11-year average in all regions. Pot fishing effort was similar to that seen in the last 8 or 9 years in all regions (Olson 2009a, 2009b, 2009c, 2009d).
- The number of pot and trawl vessels remained similar in 2008, but the number of hook and line vessels increased slightly (Hiatt 2009).

References

Contributions in the Ecosystem Considerations for 2010 report that are cited in this summary are listed below and available at: http://access.afsc.noaa.gov/reem/ecoweb/index.cfm

Bond, N., and J. Overland. 2009. North Pacific climate overview. P. 29-39.

Ladd, C. 2009. Eddies in the Gulf of Alaska. P. 40-41.

Batten, S. 2009. Continuous plankton recorder data in the northeast Pacific. P. 63-66.

Hebert, K. and S. Dressel. 2009. Southeastern Alaska herring. P. 71-77.

Martin, M. 2009a. Gulf of Alaska survey bottom temperature analysis. P. 44-46.

Martin, M. 2009b. Forage species – Gulf of Alaska. P. 67-68.

Mueter, F.J. 2009. Total annual surplus production and overall exploitation rate for groundfish. P. 159-161.

Urban, D. 2009. Gulf of Alaska small mesh trawl survey trends. P. 98-100.

Worton, C. 2009. ADF&G Gulf of Alaska trawl survey. P. 93-98.

Hiatt, T. 2009. Groundfish fleet composition. P. 170-171.

Olson, J. 2009a. Hook and line (longline) fishing effort in the Gulf of Alaska, Bering, Sea and Aleutian Islands. P. 129-133.

Olson, J. 2009b. Groundfish bottom trawl fishing effort in the Gulf of Alaska, Bering Sea and Aleutian Islands. P. 134-138.

Olson, J. 2009c. Groundfish pelagic trawl fishing effort in the Gulf of Alaska, Bering Sea and Aleutian Islands. P. 138-143.

Olson, J. 2009d . Pot fishing effort in the Gulf of Alaska, Bering Sea, and Aleutian Islands. P. 143-148.

Contributions in the Ecosystem Considerations for 2009 report that are cited in this summary are listed below and available at: http://www.afsc.noaa.gov/refm/docs/2008/ecosystem.pdf

Mueter, F.J. 2008. Combined standardized indices of recruitment and survival rate. 141-143.

Rooper, C.N. 2008. Distribution of rockfish species along environmental gradients in Gulf of Alaska and Aleutian Islands bottom trawl surveys. P. 62-65.

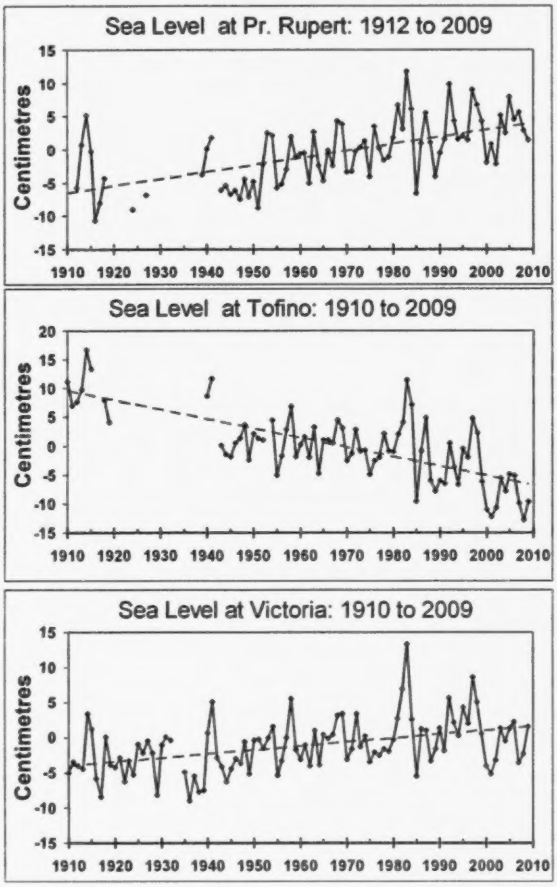
Contributions in the Ecosystem Considerations for 2008 report that are cited in this summary are listed below and at: http://www.afsc.noaa.gov/refm/docs/2007/ecosystem.pdf

Fritz, F. 2007. Pinnipeds. P. 160-167.

OUTER COAST OF VANCOUVER ISLAND, AND THE CENTRAL AND NORTH COAST

A CENTURY OF SEA LEVEL MEASUREMENTS IN BRITISH COLUMBIA

William Crawford, Fisheries and Oceans Canada


Sea Level at Pr. Rupert: 1912 to 2009

Sea Level at Tofino: 1910 to 2009

Sea Level at Victoria: 1910 to 2009

The Canadian Hydrographic Service monitors sea level along the coast. The records at left show annual deviations from long-term average levels at three ports. Two ports have records that now span 100 years. The last data point is the annual average for 2009. Dashed red lines show the linear trend.

Winter winds from the west dropped sea levels below normal at Tofino and Victoria in 2007 and 2008. These westerly winds were associated with La Niña conditions, which ended in spring 2009. Sea levels at Victoria and Tofino in 2009 rose toward the long-term average, adjusted for the trend over the past 100 years. The annual average of sea level at Prince Rupert declined somewhat from its 2008 level.

Figure 1. Graphs of annual-averaged sea levels at three British Columbia Ports. Average linear trends are plotted as red dashed lines.

The linear trends at each port are listed below (in cm/century):

Prince Rupert +10	Victoria +6	Tofino -16

Tectonic motion is lifting the land at Tofino faster than sea level is rising, so local sea level is actually dropping at a rate of 16 cm per 100 years. The next big Cascadia Subduction Zone earthquake could drop the land at Tofino and along the west side of Vancouver Island by as much as a metre, and also send a major tsunami toward the BC coast.

Global sea levels rose by 17± 5 cm in the 20th century. Satellite observations since 1993 indicate sea levels are presently rising at a rate of 30 cm per century. The Intergovernmental Panel on Climate Change (IPCC 2007) predicts sea level to rise by 20 to 60 cm over the 21st century, but recent observations of ice melt in Greenland and Antarctica suggest these projections might be too low.

Reference

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. 2008. An examination of the factors affecting relative and absolute sea level in coastal British Columbia. Can. Tech. Rep. Hydrogr.Ocean Sci. 260: v + 49 p.

LONG-TERM TEMPERATURE AND SALINITY AT BC LIGHTHOUSES

Peter Chandler, Fisheries and Oceans Canada

Temperature and salinity are measured daily at the first daylight high tide at 13 lighthouse stations as part of the DFO Shore Station Oceanographic Program.

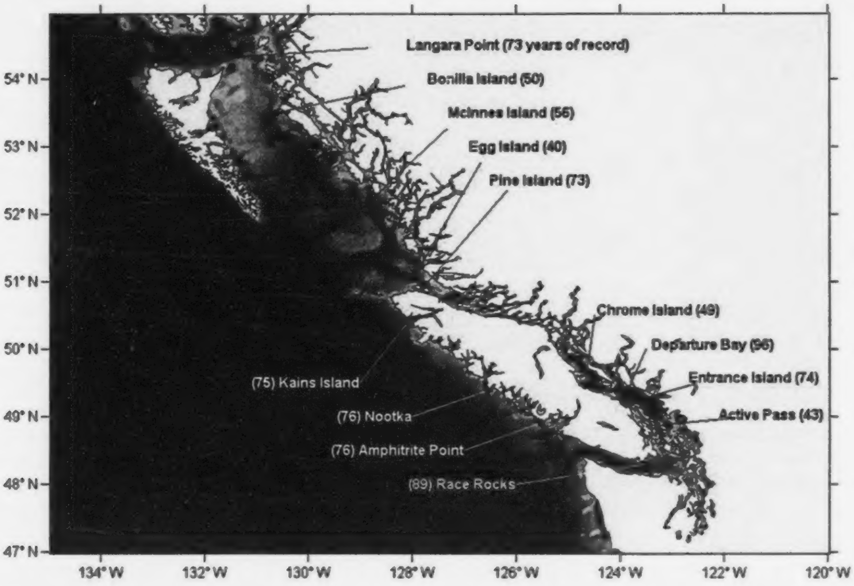


Figure 1. The 13 stations presently in the network and the number of years of data in the record.

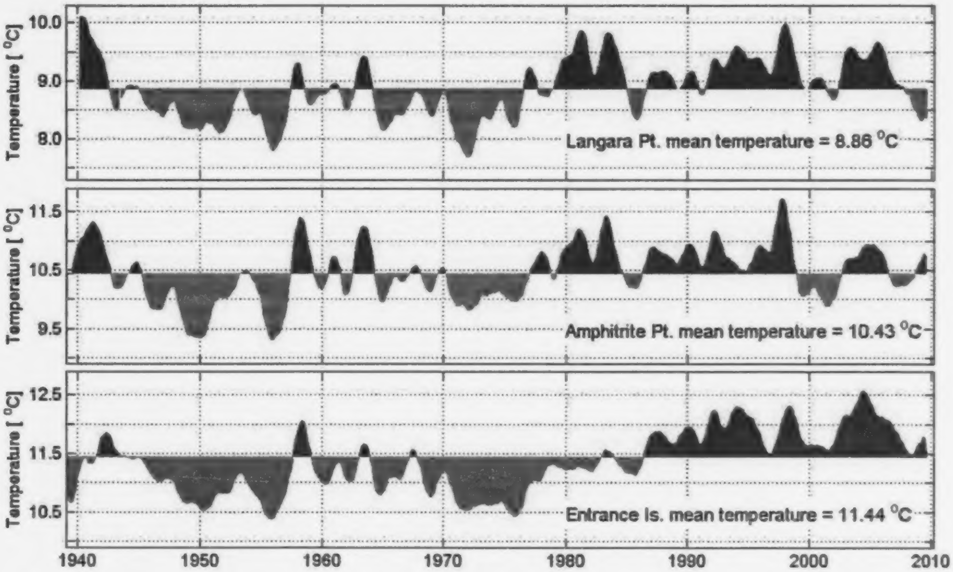


Figure 2. Long-term time series of monthly temperature, averaged over 12 months, at stations representing North Coast, West Coast and Strait of Georgia. Positive (negative) anomalies from the long-term mean (1936-2009) are shown in red (blue).

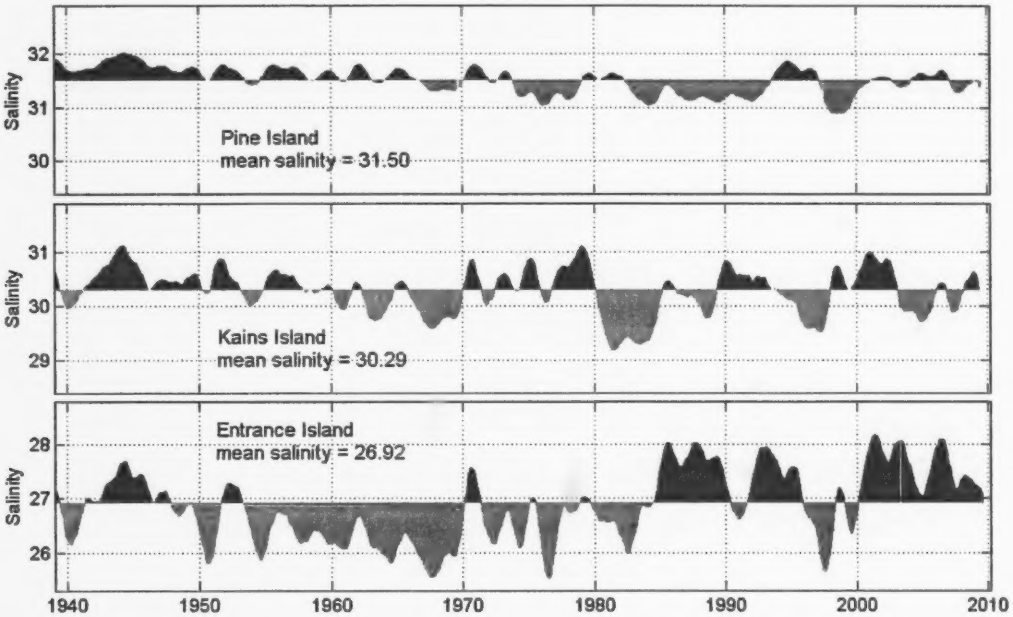


Figure 3. Long-term time series of monthly salinity, averaged over 12 months, at stations representing North Coast, West Coast and Strait of Georgia. Positive (negative) anomalies from the long-term mean (1936-2009) are shown in red (blue).

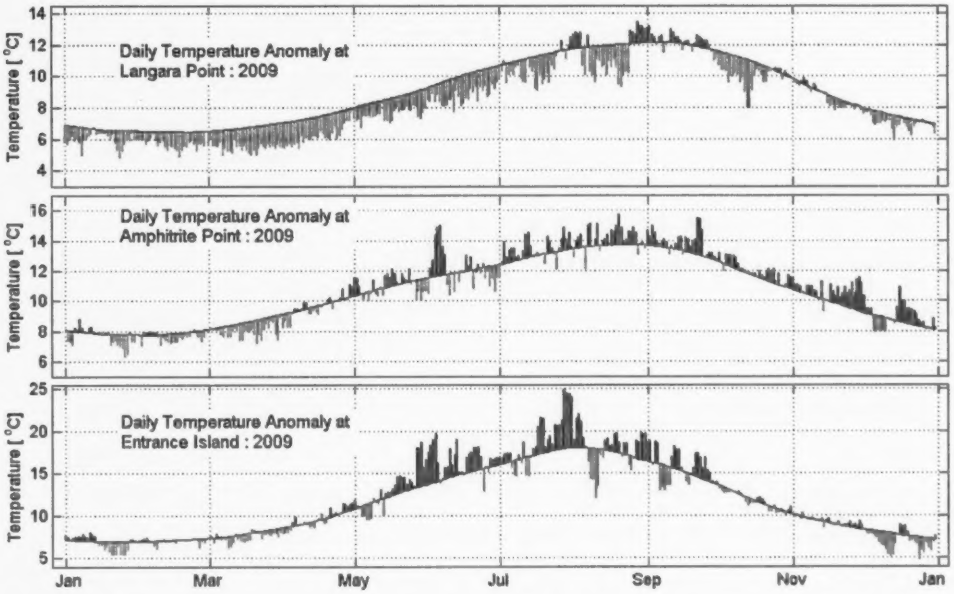


Figure 4. Daily temperatures and the annual cycle (calculated from the 1971-2000 data) representing North Coast, West Coast and Strait of Georgia. A generally cooler-than-normal spring led to a warmer-

than-usual summer (less warming in northern waters). Warmer temperatures continued to the end of 2009 along the West Coast, but not on the North Coast or to the same degree in the Strait of Georgia.

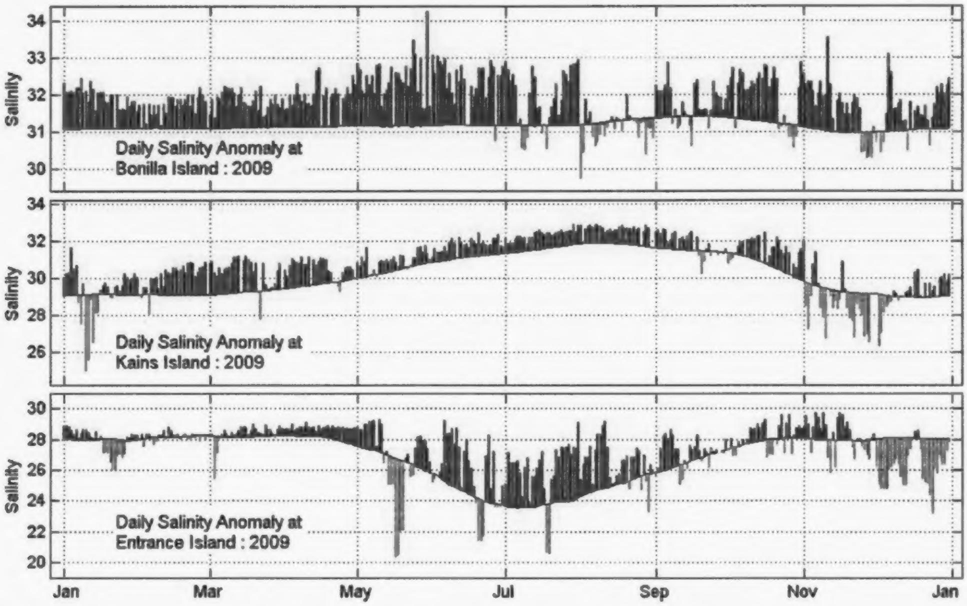


Figure 5. Daily salinity and the annual cycle (calculated from the 1971-2000 data) representing North Coast, West Coast and Strait of Georgia. Generally saltier conditions were observed throughout the region with evidence of some freshening occurring during the latter part of the year, particularly in the Strait of Georgia.

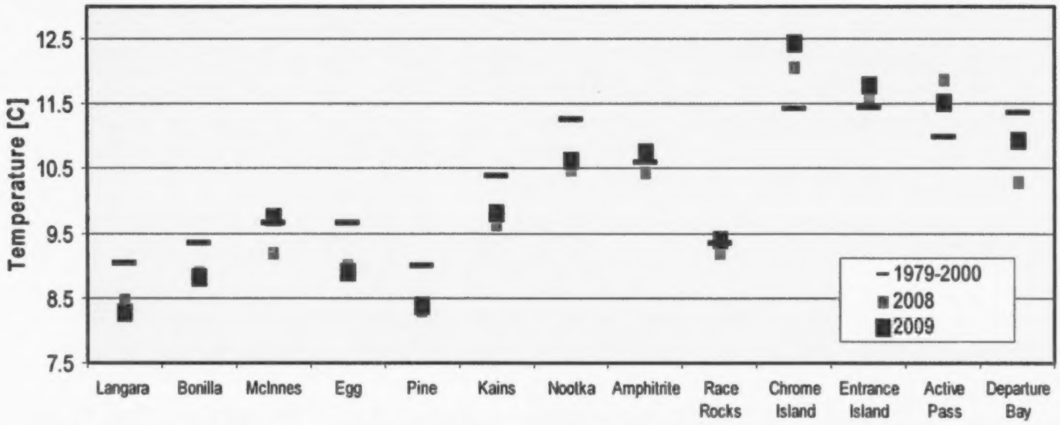


Figure 6. The mean daily sea surface temperature in 2008 and 2009, and the annual mean calculated from the 1971-2000 data. Seven stations continue to show lower-than-normal temperatures. Temperatures changed from below normal in 2008 to above normal in 2009 at three stations. Nine of the 13 stations show warmer water in 2009 than in 2008.

Links: BC Seawater sampling at Lighthouses
www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.htm

CHANGES IN OXYGEN CONCENTRATIONS ON THE CONTINENTAL SHELF

Bill Crawford[1], Richard Pawlowicz[2] and Ron Tanasichuk[1]
[1]Fisheries and Oceans Canada [2]Earth & Ocean Sciences, University of British Columbia

Previous studies have observed steady declines in oxygen concentrations in waters deeper than 150 metres at Ocean Station Papa, located about 1500 km west of Vancouver Island (Whitney, 2009). Very low oxygen concentrations were discovered earlier this century on the continental shelf of Oregon and Washington State. The low oxygen levels off Oregon led to deaths of local shellfish in summer.

In the past decade we have observed low oxygen concentrations near ocean bottom somewhat more frequently off the west and north coasts of Vancouver Island however, we have received no reports of shellfish mortalities.

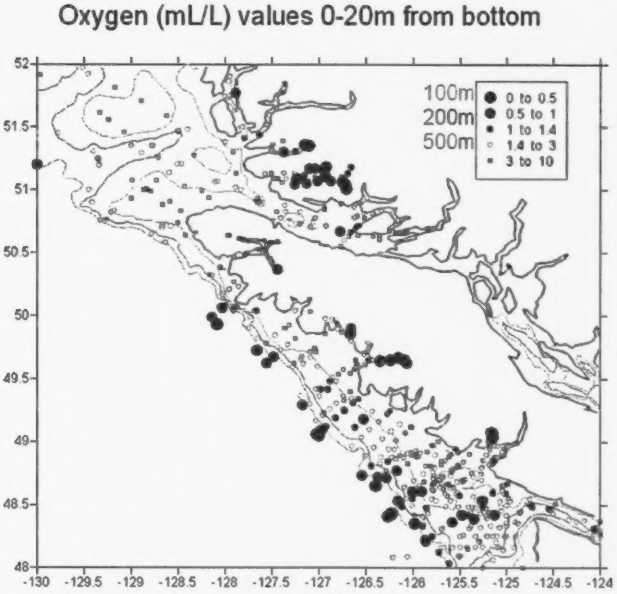


Figure 1. Concentration of oxygen in summer (July to September) within 20 metres of ocean bottom, as determined by titrated samples on research cruises of Fisheries and Ocean Canada. Samples were collected from 1979 to 2009. Units are milliliters per litre. Coloured contours show 100, 200 and 500 m depths.

The concentration of oxygen in bottom waters of the Vancouver Island continental shelf is normally low due to oxidation of organic matter there, and also to low levels of O_2 in source waters farther offshore. We monitor these bottom waters regularly in summer to see if oxygen concentrations are declining.

Two figures at left reveal the present status. The top panel of Figure 1 presents measurements in July to September of oxygen within 20 metres of ocean bottom, based on archives of water properties held by Fisheries and Oceans Canada, Pacific Region.

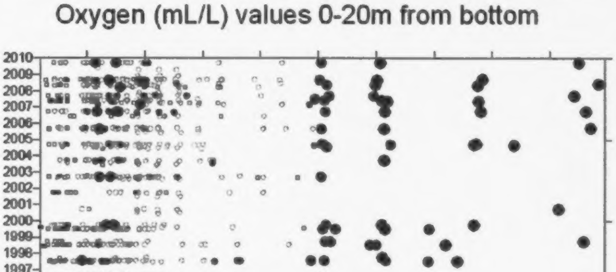


Figure 2. Changes in concentration of oxygen in summer (July to September) in waters near Vancouver Island within 20 metres of the ocean bottom. Data from inlets are not included. Each point is plotted at the depth of ocean where sampling took place, and in the year of sampling. Oxygen units are milliliters per litre.

Levels below 0.5 millilitres per litre (ml l^{-1}) in Fig. 1 are plotted in black. These are labelled as "hypoxic" and are harmful to many marine species. Levels close to hypoxic (0.5 to 1.0 ml l^{-1}) are plotted in red. Hypoxic concentrations in Figure 1 are all in regions where the total water depth is deeper than 200 m or at the bottom of inlets where hypoxic is a normal, natural state.

The right panel presents changes in oxygen over the years since 1979. There are more observations of near hypoxia (red symbols, 0.5 to 1.0 ml l^{-1}) after 1997. In addition, observations of oxygen concentration between 1.0 and 1.4 ml l^{-1} have increased since 1997 (The continental shelf is generally between 0 and 200 metres deep.) However, there are essentially no oxygen concentrations of less than 1.4 ml l^{-1} in waters less than 100 metres depth. It is this shallow depth range where hypoxic conditions led to most reports of mortality off Oregon. It appears that similar hypoxic conditions have not been observed near Vancouver Island.

Low oxygen in sub-surface waters is a natural feature along most of the west coast of the Americas. It is found at depths below 100 to 200 metres, which is as deep as wind-forced turbulence can mix oxygen from the surface. Oxygen generally declines with increasing depth below the 100 m in the Gulf of Alaska, reaching a minimum at depths near 1000 metres. Upwelling winds of summer along the west coast bring deep oceanic water to more shallow depths on the Vancouver Island shelf. These deeper waters with lower oxygen levels give rise to an oxygen minimum in summer.

The seasonal cycle is evident in a time series in Figure 3 below, collected at Swale Rock station (48.918°N, 125.200°W) during monthly surveys for zooplankton in Barkley Sound.

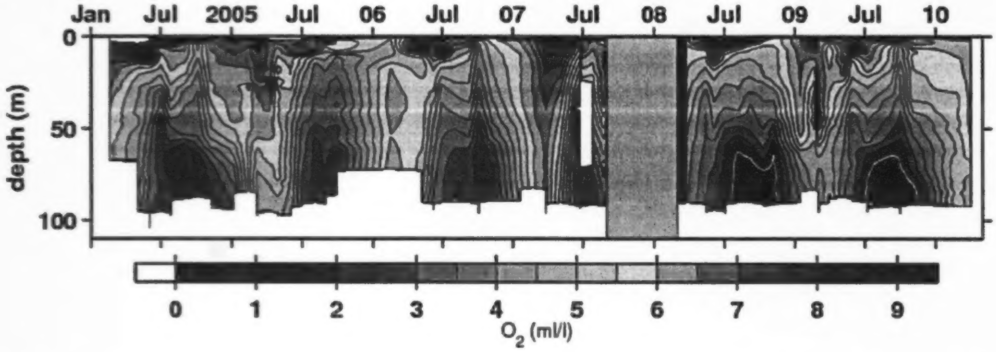


Figure 3. Contours of oxygen concentration in Barkley Sound, based on monthly sampling from February 2005 to March 2010. Depth is about 100 m. Depth of contours is determined by the deepest measurement of that month. No sampling from late summer 2008 to early in 2009.

Lowest oxygen concentration at 100 metres is in late summer and early autumn. Oxygen declines in bottom waters through the summer due to both upwelling of deep low-oxygen waters onto the shelf and to oxidation of organic material in bottom waters. When the storm season begins in October the bottom water is pushed back to deep regions, and is replaced by shallower waters with more oxygen.

Reference

Whitney, F., 2009. Spreading hypoxia in deep waters along the west coast, pages 55-56 in: Crawford, W.R. and J. R. Irvine, State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi + 121 p.

WIND-DRIVEN UPWELLING AND DOWNWELLING ALONG THE WEST COAST OF VANCOUVER IS.

Roy Hourston and Richard Thomson, Fisheries and Oceans Canada

Ocean current velocity, along with in situ water temperature and salinity, have been monitored continuously since 1985 at mooring A1 located at 48° 32' N 126° 12' W in 500 m of water on the continental slope seaward of La Pérouse Bank (Figure 1). Sea surface temperature, air temperature, wind velocity, and sea surface atmospheric pressure have been measured since 1988 at a nearby Environment Canada buoy 46206 (48° 50' N 126° 00' W). These records enable us to characterize interannual variability of surface and subsurface meteorological and physical oceanographic conditions off the west coast of Vancouver Island.

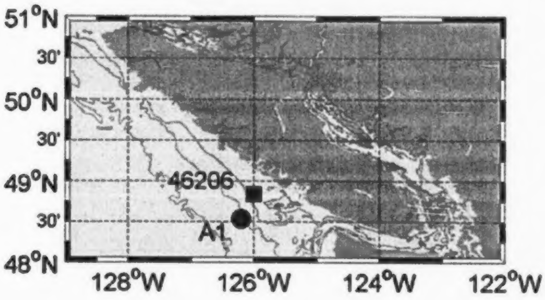


Figure 1. Locations of current meter mooring A1 and meteorological buoy 46206.

Figure 2 shows the timing of the spring transition off La Pérouse Bank according to the alongshore current velocity at 35 m depth at mooring A1 and the alongshore surface wind stress at meteorological buoy 46206. The spring transition marks the shift from poleward to equatorward ocean current and the beginning of biologically productive spring-summer upwelling conditions. The equatorward flowing shelf break current is driven by a combination of regional wind forcing and (through the effects of coastally trapped waves) remotely forced winds such that the spring transition in the current at A1 typically *leads* the wind by roughly two and a half weeks.

As documented in earlier state of the ocean reports, years having a late spring transition, such as 2003 and 2005, have been characterized by poor or significantly altered productivity in plankton, fish, and bird production. In contrast, an early spring transition time may be necessary, if not sufficient, for favourable spring/summer productivity. In 2009 the spring transition in the observed shelf-break current was in late March, near the 1990-2004 average. This indicates that 2009 should be characterized by near normal spring/summer productivity, with the possibility of better than average biological productivity along the coast.

The duration and intensity of upwelling-favourable winds are generally considered indicators of coastal productivity, due to their link to offshore Ekman transport. To gauge low-frequency variability in coastal productivity, we have summed upwelling-favourable-only winds (from NCEP/NCAR Reanalysis-1, Kistler et al., 2001) by month along the west coast of North America from 45°-60° N latitude (Figure 3). Figure 4 shows these monthly mean integrated upwelling anomalies smoothed using a five-year running mean for the period 1948-2009. Results clearly show the regime shift in the late 1970s as a sharp transition from stronger- to weaker-than-average upwelling-favourable winds. Upwelling-favourable winds have been stronger than average throughout the 2000s. In recent State of the Ocean Reports, we speculated that a repeat of the 1977 regime shift to weaker-than-average upwelling appeared imminent. However, stronger-than-average upwelling-favourable winds continued through early 2009 as far north as 55 °N (Figure 5). Also of note in this figure are the very strong upwelling-favourable winds during the summer of 2006. These results are consistent with the alongshore shelf-break current at A1 at 35 m depth which experienced a stronger equatorward component than average through 2007-2009. On the other hand, mid-2009 marked a change to stronger-than-average poleward alongshore (downwelling-favourable) flow which extends to the end of the record in fall 2009. We anticipate that our report in 2011 will be able us to say whether this marked the beginning of a sustained shift to stronger than average downwelling conditions.

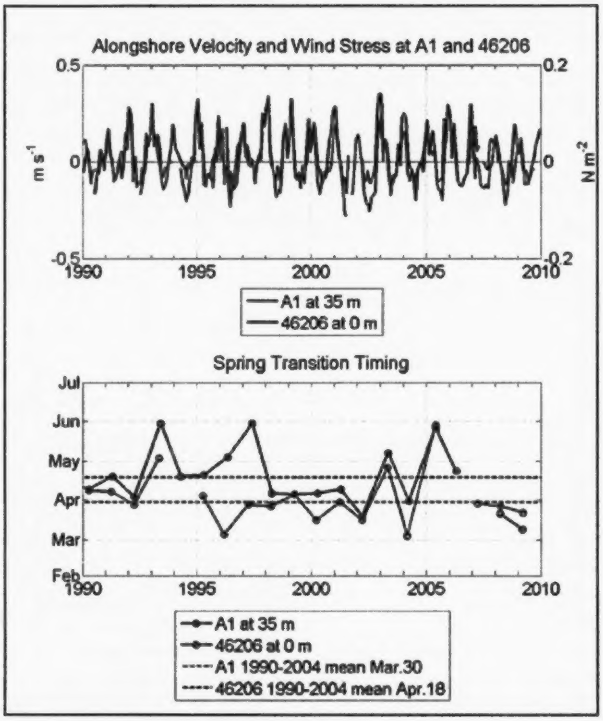


Figure 2. Spring transition timing of alongshore current velocity at mooring A1 at 35 m depth and alongshore wind stress at met buoy 46206. Spring timing corresponds to the time when the monthly mean time series crossed the zero line (poleward to equatorward) in spring. In the case of multiple spring crossings, the times were averaged to obtain one value per year. There are no estimates for current in 2006 and wind in 2007 due to instrument failures.

This year, we have also examined the downwelling-favourable winds by considering only the poleward component of the alongshore wind stress; the anomalies of the monthly poleward sums are shown in Figure 6. Here, the regime shift in the late 1970s is characterized by a transition that is latitude dependent. Southward of 48°N, the transition is from average to below-average downwelling, whereas northward of this latitude, the transition marks a change from below average to stronger-than-average downwelling. The strong El Niños of 1982-83 and 1997-98 are characterized by stronger than average downwelling; the largest anomalies and greatest spatial extent are positive, beginning in 1998 and extending over the range of latitude from 45-60°N through to the present. A more detailed (non-filtered) examination of the last six years shows mostly positive downwelling anomalies over this period, with strong (downwelling-favourable) poleward winds in the winter of 2006-2007 and stronger than average poleward winds beginning mid-year in 2009.

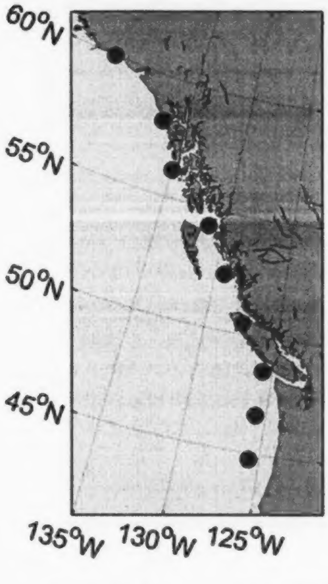


Figure 3 (left). NCEP/NCAR Reanalysis-1 coastal surface windstress grid locations.

Reference

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woolen, M. Chelliah. W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van del Dool, R. Jenne, and M. Fiorino. 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society* 82: 247–267.

Acknowledgements: NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/

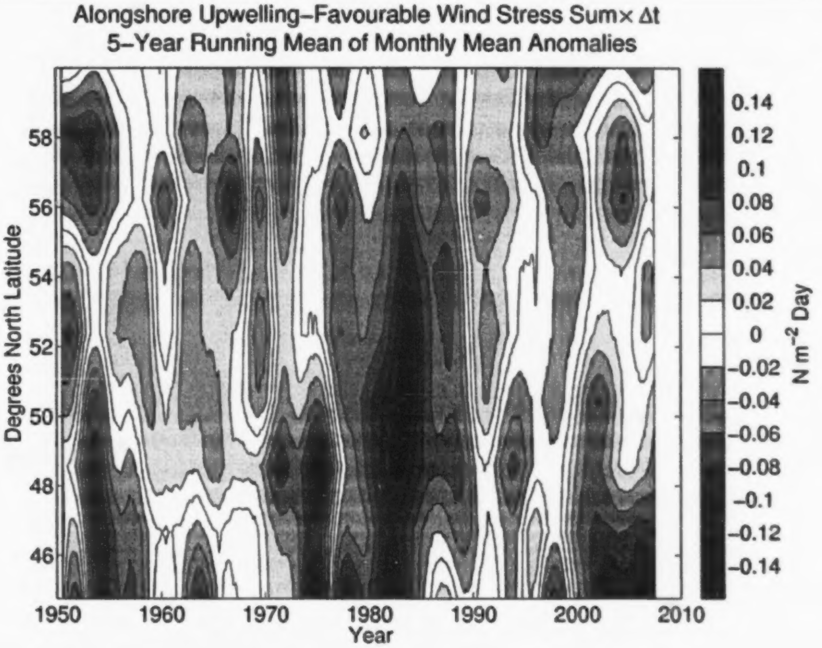


Figure 4. Five-year running means of monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45°-60° N.

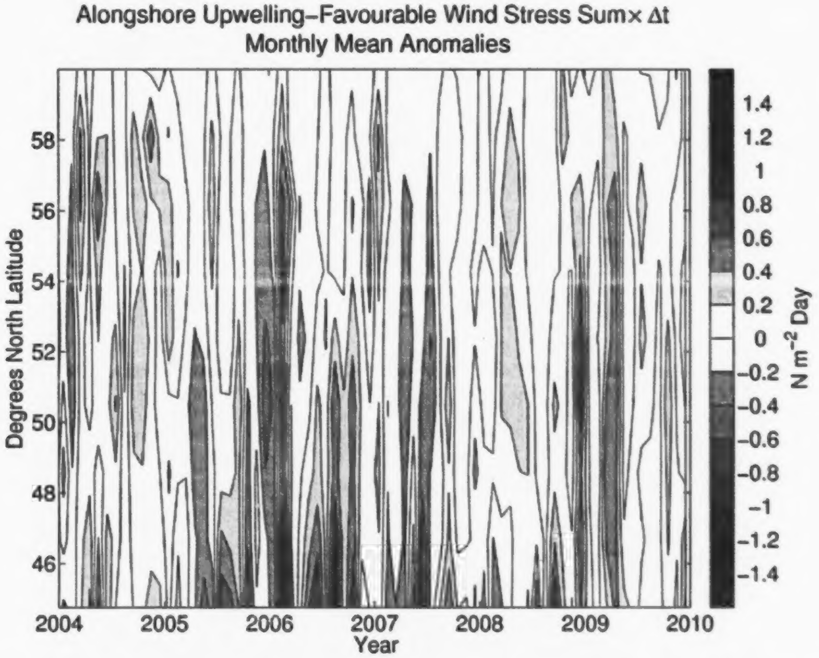


Figure 5. Recent (2004 to 2009) non-filtered monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45°-60° N.

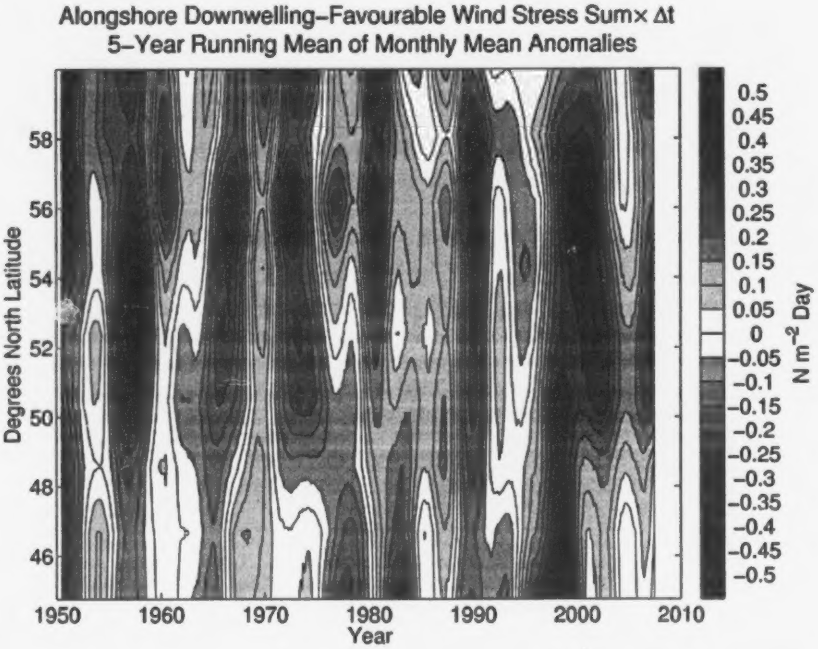


Figure 6. Five-year running means of monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45°-60° N.

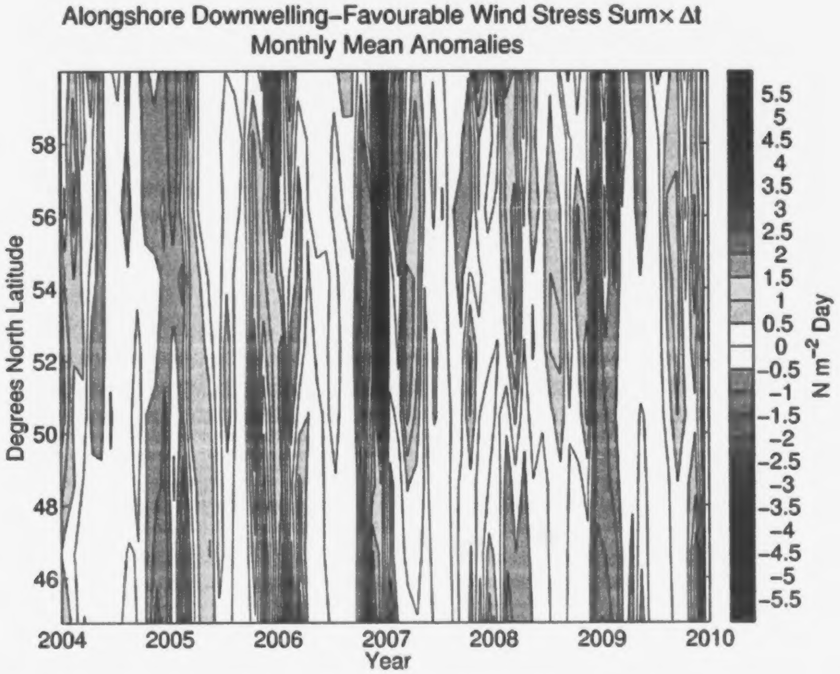


Figure 7. Recent (2004 to 2009) non-filtered monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45°-60° N.

ZOOPLANKTON ALONG THE BC CONTINENTAL MARGIN: A SPRING COOL-WATER CRUSTACEAN COMMUNITY SHIFTS TO A SUMMER AND AUTUMN WARM-WATER GELATINOUS COMMUNITY

Dave Mackas, Moira Galbraith, and Deborah Faust, Fisheries and Oceans Canada

Zooplankton time series coverage of the British Columbia continental margin extends from 1979 to present for southern Vancouver Island (SVI), from 1990 to present for northern Vancouver Island (NVI] (although with much lower sampling density and taxonomic resolution 1991-1995), and from 1998 to present for southern Hecate Strait (with some scattered earlier sampling between 1983 and 1997). The present grids of routine sampling locations are shown in Figure 1; additional locations are included in within-time-period averages when they are available. Sampling consists of vertical net hauls with black bongo nets (0.25 m^2 mouth area, 0.23 mm mesh aperture) from near-bottom to sea surface on the continental shelf and upper slope, and from 250 m to surface at deeper locations.

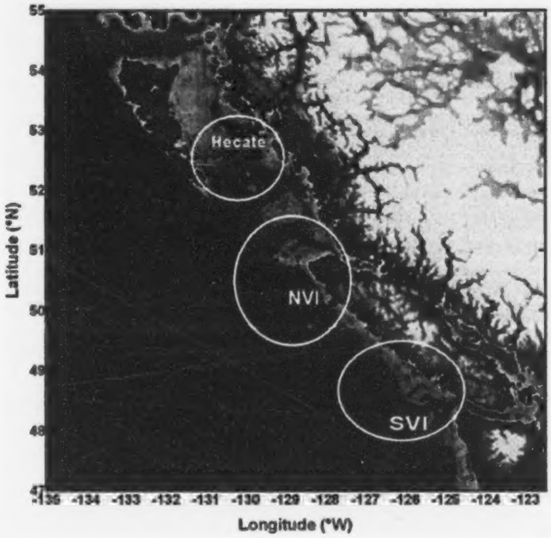


Figure 1. Zooplankton time series sampling locations (red dots) off the BC continental margin. Data are averaged within major statistical areas indicated by ovals; the SVI and NVI regions are further classified into shelf and offshore sub-regions. The PNCIMA (Pacific North Coast Integrated Management Area) includes both NVI and Hecate stat areas.

We routinely estimate abundance and biomass for more than 50 zooplankton species. For nearly all, seasonal variability is intense and somewhat repeatable from year-to-year. Figure 2 shows average seasonal cycles for the Hecate Strait region (newly reported this year; average seasonal cycles for other stat areas were reported in our previous reports). As in other regions, the dominant contributors to total biomass in spring and summer are cool-water copepods. Euphausiids increase in both relative and total biomass in late summer and autumn (as the spring euphausiid cohort matures). Chaetognaths and jellyfish are the dominant carnivorous zooplankton. Important non-crustacean herbivorous zooplankton include shelled pteropods, salps and doliolids. These groups are occasionally abundant in Hecate Strait, but on average make up less of the total biomass than they do off the outer coast of Vancouver Island.

The monthly values in each within-region average seasonal cycle (= "climatology") are weighted means (across years) of the within-year within-region spatial means during our reference period (all sampled years between 1979-2005). The climatologies provide baselines against which we can compare conditions in any single year and generate time series of interannual differences.

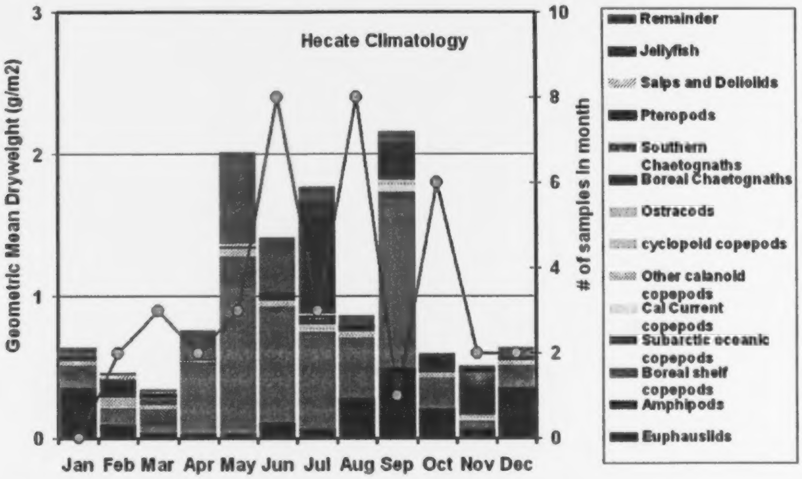


Figure 2. Average seasonal cycle in the Hecate Strait region. Bar graphs show cumulative geometric-mean dryweight biomass. Line graph shows the number of samples in each month during the baseline period. Monthly estimates based on few samples typically include data from only one or two years and are less likely to be representative of the true multi-year average.

To describe interannual variability, our approach has been to calculate within each year a within-region log scale biomass anomaly for each species and for each month that was sampled. We then average the monthly anomalies to give an annual anomaly (see Mackas 1992 & Mackas et al. 2001 for mathematical details). It is important to note that the anomalies are log scale and therefore multiplicative on linear scale: an anomaly of +1 for a given taxon means that taxon had 10X higher biomass than in the climatology; an anomaly of -1 means the biomass was 1/10th the climatology. We have learned from our own and other west coast time series (Mackas et al. 2006) that zooplankton species with similar zoogeographic ranges and ecological niches usually have very similar anomaly time series. We therefore often summarize the interannual variability of multiple species by averaging within species groups. For example, 'boreal shelf copepods' is a composite of the copepods *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*; (distribution ranges from southern Oregon to the Bering Sea); 'subarctic oceanic copepods' is a composite of *Neocalanus plumchrus*, *N. cristatus*, and *Eucalanus bungii*; (inhabitating deeper areas of the subarctic Pacific and Bering from North America to Asia); 'southern copepods' is a composite of five species with ranges centered about 1000 kilometers south of our study areas (in the California Current and/or further offshore in the North Pacific Central Gyre.

Figure 3 shows anomaly time series for these species groups (plus representative chaetognaths and euphausiids) in each of the three BC statistical areas. The range of interannual biomass variability within a species or species group is about one log unit (i.e. factor of 10), and in our regions is about 2-3 fold greater than the interannual variability of total biomass. Other features to note are the serial autocorrelation of individual time series (anomalies persist over successive years) and that, in addition to the covariation within species groups mentioned above, the strong covariation between species groups. Cool years such as the early 1980s, 1999-2002, and 2007-08 tended to have positive anomalies of boreal shelf and subarctic copepods, and northern chaetognaths. Warm intervals such as 1983, 1993-1998, and 2004-2005 tended to have negative anomalies of these taxa, but positive anomalies of southern copepods and chaetognaths. We now know that positive anomalies of the cool water zooplankton community off Vancouver Island are also associated with good regional survival and growth of juvenile salmon, sablefish, and planktivorous seabirds (Mackas et al. 2007; Trudel, personal communication 2010).

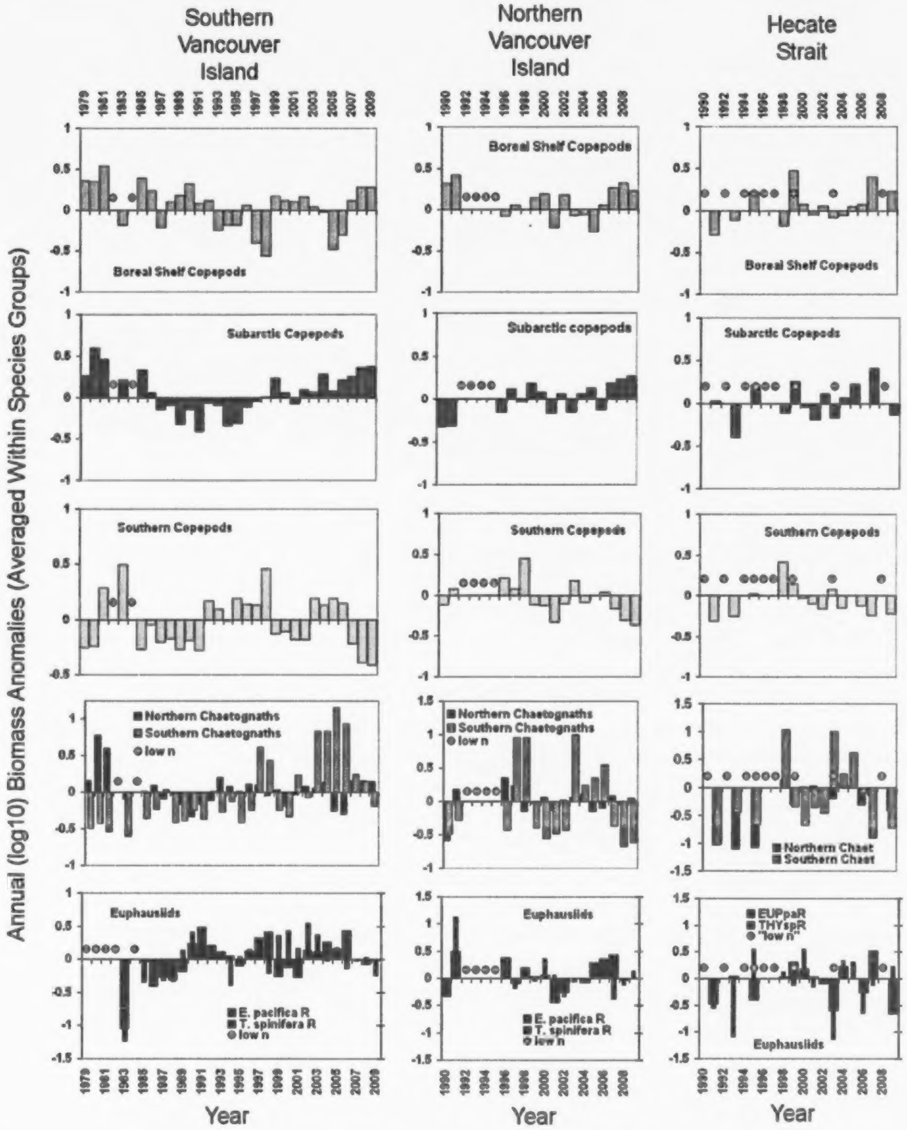


Fig. 3. Zooplankton species-group anomaly time series (vs 1979-2005 baseline) for the SVI, NVI and Hecate regions shown in Fig 1. Bar graphs are annual log scale anomalies. Circles indicate years with no or very few samples from that region. Cool years favour endemic 'northern' taxa, warm years favour colonization by 'southern' taxa.

In 2009, the annual average zooplankton anomalies suggest a persistence through the year of the cool water community that had dominated in 2007 and 2008. However, within-2009 data showed a rapid and steep transition from a spring community that was very strongly dominated by cool water crustaceans (large copepods and euphausiids) to a late summer and autumn community dominated by two warmer water non-crustacean taxa: the pteropod *Clio pyramidata*, and the doliolid *Dolioletta gegenbauri*. Southern copepods also increased from May to September, despite the fact that their usual annual maximum is during the winter downwelling season when southerly winds drive peak poleward transport from southern source regions. Figure 4 illustrates the May to September changes, and also the mean May-September biomass contributed by each of these taxonomic categories. The southern origin oceanic species all increased over the course of the 2009 growing season, while northern origin species (both oceanic and coastal) decreased. These shifts were strongest at locations farthest from shore (outer continental shelf and continental slope. Community changes on the inner continental shelf were in the same direction, but were much weaker.

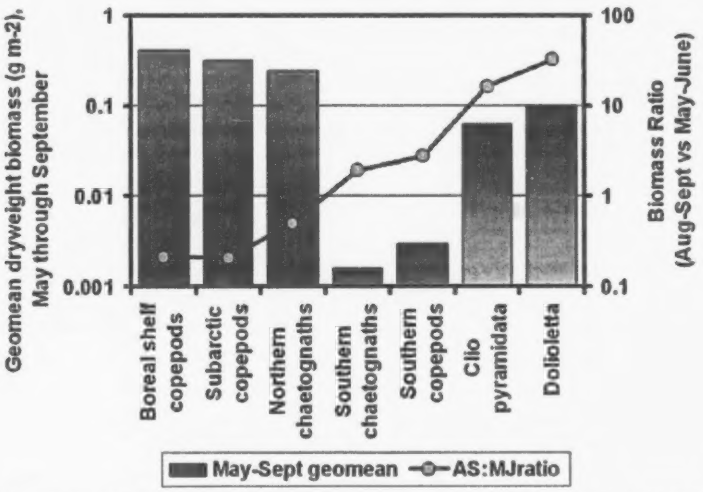


Fig 4. Intense 2009 summer transition of the zooplankton community. Line graph (AS:MJ ratio) shows the ratio of late summer-early autumn (August-September) biomass to late spring-early summer (May-June) biomass within different taxonomic categories. Column graphs show the geometric mean biomass of the same taxa across the full growing season (May-September). Northern origin cool-water taxa (blue columns) declined steeply from spring to late summer (ratio < 0.2-0.7) while southern/seaward origin warm water taxa (orange columns) increased rapidly (ratio 2-10).Data shown in these graphs are averages over all SVI and NVI regions, but the spring-to-autumn trend was strongest in the offshore sub-regions; weaker but in the same direction in the inner shelf sub-regions.

The two taxa that became the 2009 late-summer biomass dominants at outer shelf and slope sampling locations (the pteropod *Clio pyramidata*, and the doliolid *Dolioletta gegenbauri*) are both individually large (circa 1 cm body length), but are probably too large and also too gelatinous and lipid-poor to be optimal prey for summer predators such as juvenile salmon, herring, and planktivorous seabirds. Over the past 30-50 years, both *Clio* and *Dolioletta* were historically occasional biomass dominants in the southern California Current (CalCOFI sampling region) and moderately abundant-to-abundant in the adjoining deep sea (the North Pacific Central Gyre). But they were historically very rare on average, and highly intermittent in occurrence, within the northern California Current system (including off British Columbia). However, this latitudinal gradient of occurrence and dominance has changed dramatically since

~2000. Figure 5 shows time series of annual anomalies of *Clio* and *Dolioletta* over the southern Vancouver Island continental shelf break and slope. Both species were either absent or present only at very low abundance/biomass prior to 2000. Since the turn of the century, doliolids have had strong positive anomalies in most years Generally, the number of copepods decrease as the number of *Dolioletta* increase in a given area. *Clio* has remained more intermittent, but now occasionally extremely abundant. All 3 years with large positive anomalies of *Clio* have been during the past decade.

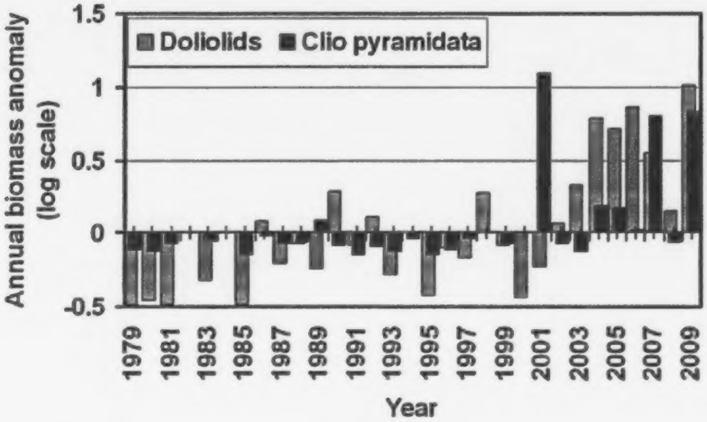


Fig. 5 Anomaly time series for large gelatinous herbivorous zooplankton off southern Vancouver Island. Graphed are doliolids (mostly Dolioletta gegenbauri*) and warm water thecosomatous pteropods (*Clio pyramidata*). Both are endemic to the mid-latitude Pacific south of the subtropic-subarctic transition zone, but occasionally invade the eastern subarctic Pacific. The frequency and intensity of invasion has increased dramatically since about 2000.*

Since 2000, both *Dolioletta* and *Clio* have also shown increased occurrence rate and abundance at stations along the oceanic Line P transect. This suggests a large scale poleward displacement of their northern distribution boundary covering much of the eastern North Pacific (i.e. not confined to the Alaska and California boundary current regions). In 2009, the large positive biomass anomalies appeared earlier along Line P than they did along the Vancouver Island margin. Eastward zonal advective transport by an intensified North Pacific Current (see Freeland ARGO report, this issue) may have been the main mechanism by which these species colonized the Vancouver Island continental margin in 2009.

References:

Mackas, D.L. 1992. The seasonal cycle of zooplankton off southwestern British Columbia: 1979-89. *Can. J. Fish. Aquat. Sci.* 49: 903-921.

Mackas, D.L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warming ocean: recent evidence from the North Pacific. *Progr. Oceanogr.* 75: 223-252.

Mackas, D. L., W. T. Peterson, M. D. Ohman, and B. E. Lavaniegos 2006, Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005, *Geophys. Res. Lett.*, 33, L22S07, doi:10.1029/2006GL027930.

Mackas, D.L., R.E. Thomson and M. Galbraith. 2001. Changes in the zooplankton community of the British Columbia continental margin, and covariation with oceanographic conditions, 1985-1998. *Can. J. Fish. Aquat.* Sci. 58: 685-702.

OCEAN CONDITIONS OFF OREGON IN 2009.

Bill Peterson, Northwest Fisheries Science Centre,
National Oceanic and Atmospheric Administration, USA

The trend of cold ocean conditions in the northern California Current off Oregon that began in 2007 continued through 2008 and into the first half of 2009. However conditions began to change in June 2009 as upwelling winds relaxed and the ocean began to warm significantly, leading to detrimental changes in the pelagic food web and likely high mortality of juvenile salmonids. Among the better indicators of these changes include the Multivariate ENSO Index (MEI), the Pacific Decadal Oscillation (PDO), and local sea surface temperature (SST).

The MEI, which had been negative (La Niña) since June 2007, became positive in May 2009, indicating that the extended La Niña had ended (Figure 1). Subsequent to the change in phase of the MEI, NOAA issued a warning that an El Niño event was developing at the Pacific equator, and a full El Niño set in by summer 2009. As a result of the developing El Niño it is likely that an atmospheric teleconnection between the Pacific equator and the northern North Pacific led to a weakening of the PDO beginning in June 2009. The PDO then turned positive (warm phase) in August. SST measured at NOAA Buoy 46050 (17 miles off Newport OR) showed + 0.9°C anomalies in August, 1.4°C in September and 0.7, 0.6 and 1.2°C in October, November and December 2009. These anomalies are not particularly strong when examined in the context of measurements made over the past decade or so: Figure 1 clearly shows that the warming was far less than observed during strong 1997-1998 El Niño event and less than both the "moderate" El Niño event of 2002, and the "weak" El Niño events of 2004 and 2006. Upwelling along the Oregon coast also became weak in August with either calm conditions or southwest winds dominating the meteorological conditions.

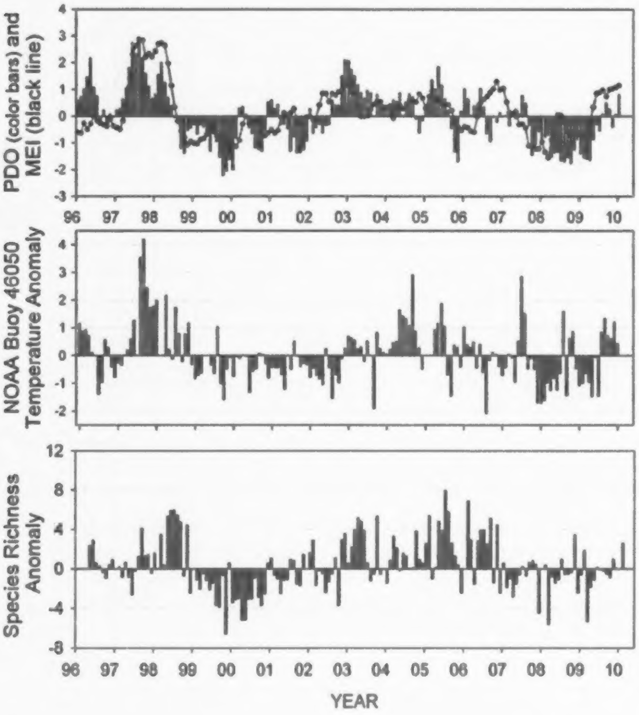


Figure 1. ***Upper Panel****. Time series of the Pacific Decadal Oscillation (PDO) and Multi-variate ENSO Index (MEI) from 1996 to early 2010.* ***Middle Panel****. Time series of monthly average sea surface temperature anomalies measured at the NOAA Buoy 46050 located 17 miles off Newport Oregon. Anomaly is calculated from the base period of 1991-2008.* ***Lower Panel****. Time series of the anomaly of monthly averaged species richness of copepods collected at a baseline station located 9 km off Newport Oregon. Species richness is the number of copepod species in a given zooplankton sample. Note that a persistent change in the sign of MEI is usually followed by change in sign of the PDO; note also that SST and copepod species richness follow MEI and PDO with a few months time.*

Another indicator of a change in ocean conditions during 2009 was ocean temperature and salinity measured on the continental shelf near Newport, Oregon, at a depth of 50 m at a baseline station nine km from the coast (water depth = 62 m) during our biweekly monitoring cruises. Averaged over the May-September period, warmer and fresher water was seen (Figure 2). The presence of warm water of lower salinity was consistent with the lack of consistent and strong upwelling in indicating that surface waters from offshore dominated the continental shelf of Oregon in 2009.

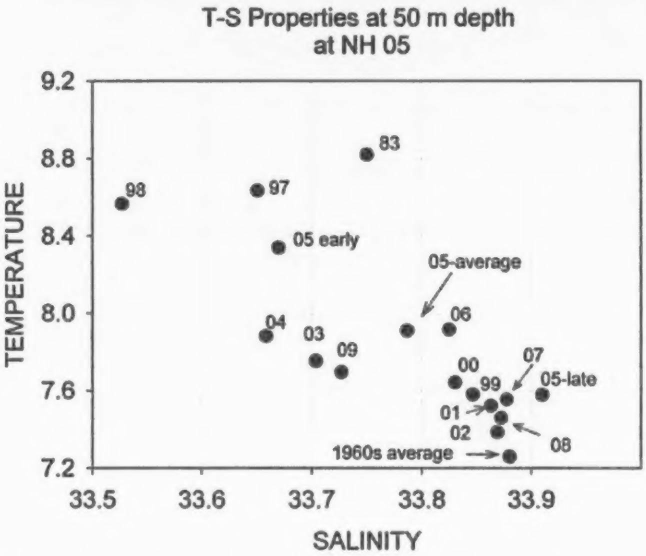


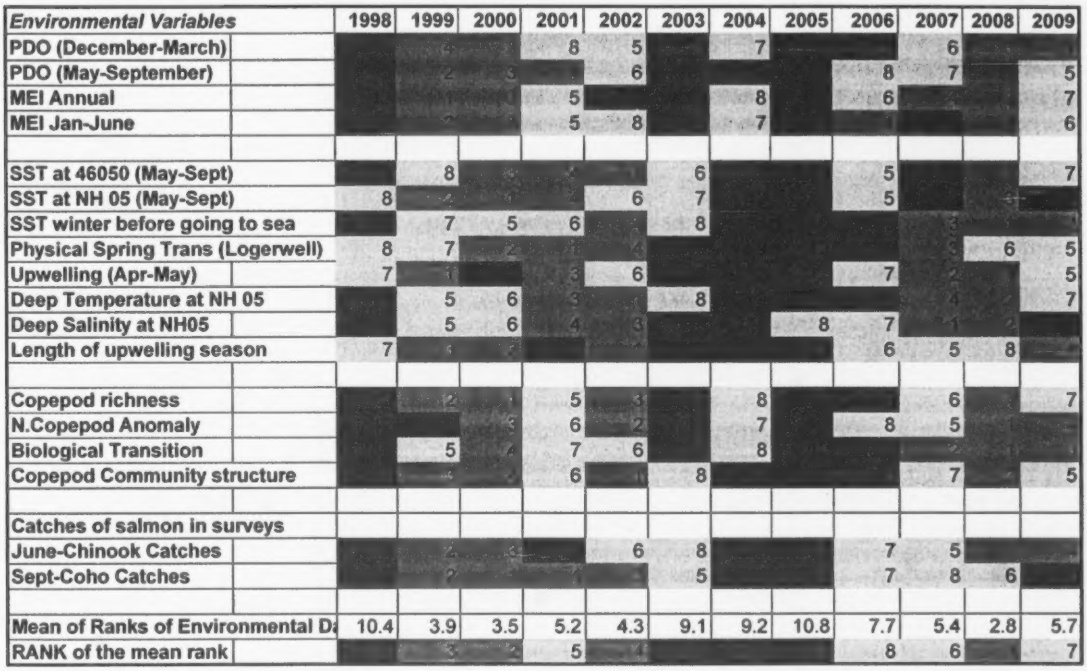
Figure 2. Temperature and salinity measured at a depth of 50 m at a baseline station off Newport Oregon located 9 km from shore. Water depth at this station is 62 m. Each data point is an average of data collected over the months May-September and includes from 12-18 CTD casts over that time period. Note that the summer of 2009 resembles the "fresher" summers of 1997, 2003, 2004 and 2005.

Copepod species richness is another indicator of seasonal and interannual variations in ocean conditions and biodiversity. (Species richness is simply the number of copepod species observed in biweekly plankton samples.) Monthly average values for copepod species richness continue to track quite closely with the PDO and SST (Figure 1) such that when the PDO is negative, the copepod community is dominated by only a few cold–water, subarctic species. Conversely, when the PDO is positive, SST is warm, and the copepod community is dominated by a greater number of warm–water, subtropical species. During 2009, we found moderately low biodiversity, but certainly no indication of an influx of an anomalously high number of subtropical species. This suggests that the warming observed in 2009 was localized, and not due to any northward transport of subtropical waters during summer or autumn of 2009 as a result of the El Niño event.

Northern copepod biomass anomalies for the year 2009 were also fairly high, 0.45, similar to values seen in 2007 (0.50), but less than values in 2008 (0.75).

Catches of juvenile spring Chinook salmon off the Washington and Oregon coast in June 2009 were the 4th highest of our 12 years of sampling, whereas catches of Coho in September 2009 were the lowest of the 12 year time series.

These data are summarized in the form of a stoplight chart (Figure 3, next page) which indicates good, average or poor ocean conditions, from the viewpoint of juvenile Chinook and Coho salmon from rivers of of Washington and Oregon. The year 2009 ended as being a low-average year, ranking 7th out of the 12 years over which we have data to complete the chart.



Environmental Variables	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
PDO (December-March)	[illegible]	4	2	8	5	[illegible]	7	[illegible]	[illegible]	6	[illegible]	[illegible]
PDO (May-September)	[illegible]	2	3	[illegible]	6	[illegible]	[illegible]	[illegible]	8	7	[illegible]	5
MEI Annual	[illegible]	[illegible]	[illegible]	5	[illegible]	[illegible]	8	[illegible]	6	[illegible]	[illegible]	7
MEI Jan-June	[illegible]	[illegible]	[illegible]	5	8	[illegible]	7	[illegible]	[illegible]	[illegible]	[illegible]	6
SST at 46050 (May-Sept)	[illegible]	8	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	5	[illegible]	[illegible]	7
SST at NH 05 (May-Sept)	8	[illegible]	[illegible]	[illegible]	6	7	[illegible]	[illegible]	5	[illegible]	[illegible]	[illegible]
SST winter before going to sea	[illegible]	7	5	6	[illegible]	8	[illegible]	[illegible]	[illegible]	3	[illegible]	[illegible]
Physical Spring Trans (Logerwell)	8	7	2	[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	3	6	5
Upwelling (Apr-May)	7	1	[illegible]	3	6	[illegible]	[illegible]	[illegible]	7	2	[illegible]	5
Deep Temperature at NH 05	[illegible]	5	6	3	[illegible]	8	[illegible]	[illegible]	[illegible]	4	[illegible]	7
Deep Salinity at NH05	[illegible]	5	6	4	3	[illegible]	[illegible]	8	7	1	2	[illegible]
Length of upwelling season	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6	5	8	[illegible]
Copepod richness	[illegible]	2	1	5	3	[illegible]	8	[illegible]	[illegible]	6	[illegible]	7
N.Copepod Anomaly	[illegible]	[illegible]	3	6	2	[illegible]	7	[illegible]	8	5	1	[illegible]
Biological Transition	[illegible]	5	4	7	6	[illegible]	8	[illegible]	[illegible]	2	1	[illegible]
Copepod Community structure	[illegible]	[illegible]	[illegible]	6	[illegible]	8	[illegible]	[illegible]	[illegible]	7	[illegible]	5
Catches of salmon in surveys												
June-Chinook Catches	[illegible]	2	[illegible]	[illegible]	6	8	[illegible]	[illegible]	7	5	[illegible]	[illegible]
Sept-Coho Catches	[illegible]	2	[illegible]	[illegible]	[illegible]	5	[illegible]	[illegible]	7	8	6	[illegible]
Mean of Ranks of Environmental D:	10.4	3.9	3.5	5.2	4.3	9.1	9.2	10.8	7.7	5.4	2.8	5.7
RANK of the mean rank	[illegible]	3	2	5	4	[illegible]	[illegible]	[illegible]	8	6	[illegible]	7

Figure 3. Stoplight chart showing the ranks of environmental variables that define ocean conditions from the viewpoint of Chinook and Coho salmon entering the ocean from rivers of Washington and Oregon. A rank of "1" indicates the best ocean conditions; rank of "12" the worst ocean conditions measured over the past 12 years (1998-2009). The rank of the mean rank (last row of numbers) succinctly summarizes ocean conditions among years. Rankings of 1 to 4 are green; 5 to 8 are yellow; 9 to 12 are red. Colours follow a "stop light" sequence.

EUPHAUSIIDS AND HAKE ON THE WEST COAST OF VANCOUVER ISLAND: MORE FOOD FOR COHO AND HERRING BUT NOT SOCKEYE, AND DECLINING HAKE PREDATION.

Ron Tanasichuk, Fisheries and Oceans Canada

This report summarizes results from a series of studies designed to test hypotheses about the effects of variations in characteristics of fish populations, prey biomass, competitive fish biomass and predatory fish biomass on the variability of biomass of Pacific herring (*Clupea pallasi*), and returns of wild Coho (*Oncorhynchus kisutch*) and Sockeye (*O. nerka*) salmon for the west coast of Vancouver Island (WCVI). Information on the characteristics of the herring population (egg deposition, catch, age composition) and salmon populations (catch, spawner abundance, smolt production, age composition) comes from various DFO monitoring programmes. Zooplankton and euphausiids (krill) have been monitored since 1991 to provide observations of prey availability. The studies have taken advantage of a time series of hydro-acoustic surveys of Pacific hake (*Merluccius productus*) (e.g. Fleischer et al. 2005) to test the effects of competition (see Tanasichuk 1999) and predation (Tanasichuk et al. 1991) on herring.

Zooplankton/euphausiid monitoring programme

Zooplankton and euphausiid species compositions and biomasses have been monitored in Barkley Sound since 1991 (see Tanasichuk 1998). The information presented here focuses on the euphausiid *Thysanoessa spinifera* because it is the most important prey item for Pacific herring (Tanasichuk *in press),* Coho salmon (*O. kisutch*) (Tanasichuk 2002) and Sockeye salmon (Tanasichuk and Routledge *in press*). The time series of the logarithm of the median biomass for *T. spinifera* in Barkley Sound are presented in Fig. 1.

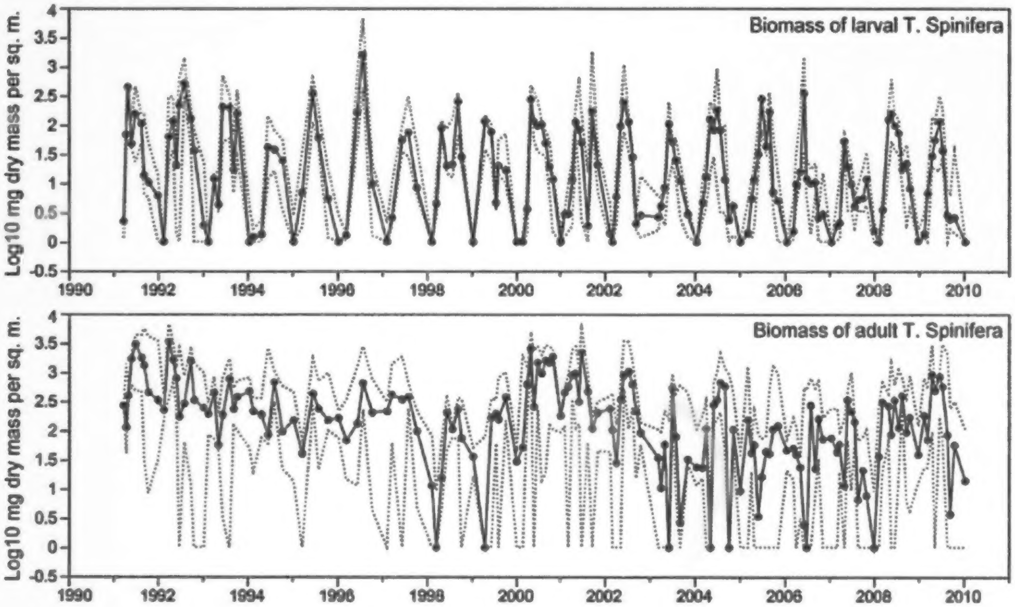


Figure 1. The 1991-2009 time series of ***larval*** *(top panel, <10 mm long) and* ***adult*** *(bottom panel > 9 mm long) T. spinifera biomass. Median larval and adult biomasses in 2009 were the lowest and at the average respectively in the time series; larval biomass decreased by 72% and adult biomass increased by 245% from 2008. Closed circles – median biomass; dashed lines – minimum or maximum biomass.*

Seasonal patterns of abundance in 2009 appeared to be typical although biomass estimates were sometimes low. Larval biomass fluctuations reflected Tanasichuk (1998)'s observation that T. spinifera spawns a number of times between early spring and late summer. Adult biomass seasonality reflected the dominance of over-wintering adults early in the year and the production of new adults later in the year. Median annual biomass of larvae and adults in 2009 was the lowest and at the average respectively in the 19-year time series. Annual biomass estimates are misleading in terms of describing fish prey availability because different fish species require specific sizes of *T. spinifera* at apparent critical periods in their life history. A crucial factor for herring is the biomass of *T. spinifera* greater than 17 mm in August when growth is most rapid. The biomass of *T. spinifera* greater than 19 mm in August of the first marine year is correlated with return variability of Carnation Creek coho. The variation in return of Somass River Sockeye is explained by variations in the biomass of 3-5 mm *T. spinifera* in May, when the juveniles are migrating through Barkley Sound to the continental shelf.

Pacific hake hydro-acoustic survey

Pacific hake dominates the pelagic biomass in summer and is potentially the most important predator of young herring and salmon. The 1999 hake year-class was quite strong. In 2004, hake from this year-class became large enough to start consuming fish. Results from the 2007 Joint Canada-US hake coast-wide hydro-acoustic survey indicate that hake biomass was declining because of gradual disappearance of the 1999 year-class and no strong subsequent recruitments. Impacts of a potentially significant and newly-arrived predator, Humboldt squid (*Dosidicus gigas*) are unknown; currently these animals are indistinguishable hydro-acoustically from hake and impacted the hake acoustic biomass estimates in 2009.

West Coast Vancouver Island (WCVI) herring

Variation in the biomass of this herring stock is a consequence of variations in the number of new (recruit, age 3 fish) spawners, size of recruit fish, adult growth and adult survival rates. Results of a multiple regression analysis show that 94% of the variation in recruitment of WCVI herring can be explained by variations in the biomass of *T. spinifera* during each of the first three years of herring life and piscivorous (fish-eating) hake biomass during the first year of herring life (Tanasichuk, *in press*) This relationship is shown in Figure 2.

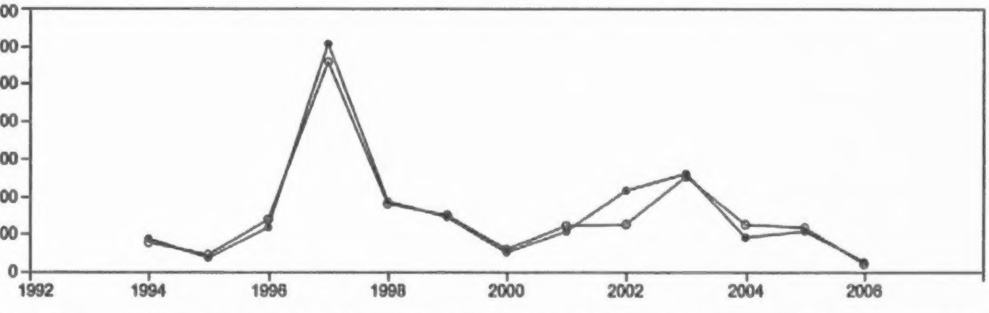


Figure 2. Observed (closed circles) and predicted (open circles) number of age 3 herring. Predicted values are estimated from the multiple regression analysis.

Tanasichuk (*in prep.*) found that *T. spinifera* biomass variation in the first and third years of life explains 68% of the variation in size of recruit herring (Fig. 3). Fish size at the beginning of the growth season explains most (63%) of the variation in the growth of adult fish; no significant effect of prey biomass was detected. The effects of recruit size on size of adult herring are detectable to age 7. Therefore, conditions affecting growth of recruit herring affect subsequent size for most of the adult life. Results for age 4 herring, typically the dominant age of adults, are presented as an example (Fig. 4).

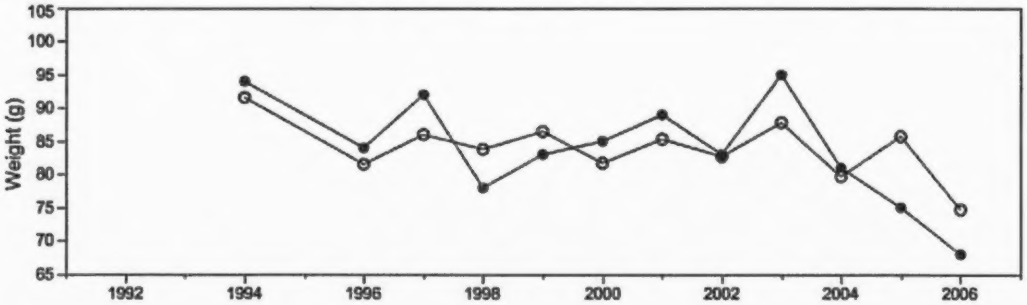


Figure 3. Observed (closed circles) and predicted (open circles) weight of age 3 herring. Predicted values are estimated from the multiple regression analysis.

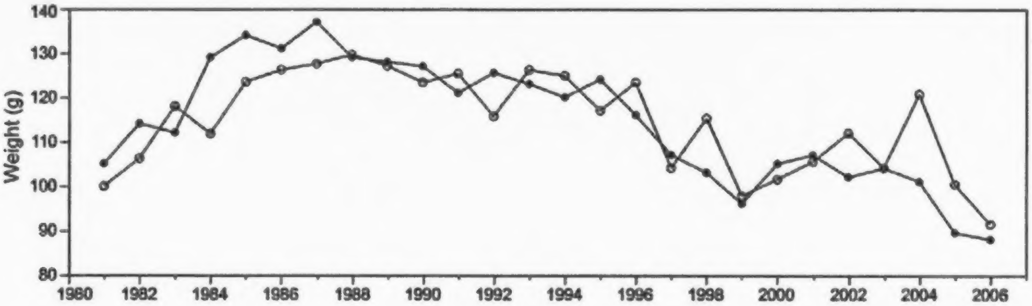


Figure 4. Observed (closed circles) and predicted (open circles) weight of age 4 herring. Predicted values are estimated from the multiple regression analysis.

Adult herring survival rates decrease with age and increase as *T. spinifera* biomass increases (Tanasichuk *submitted*). Age and *T. spinifera* biomass explain 58% of the variation in survival rate for adult WCVI herring. Figure 5 shows the comparison of observed and predicted survival rates for age 4 fish.

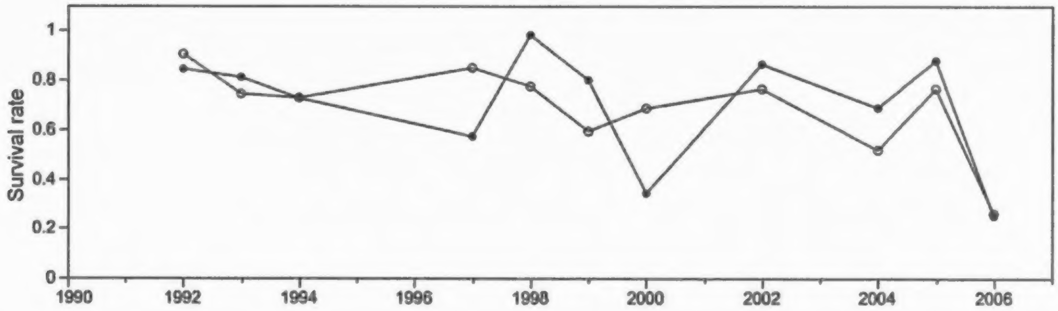


Figure 5. Observed (closed circles) and predicted (open circles) survival of age 4 herring. Predicted values are estimated from the multiple regression analysis.

Carnation Creek coho

Carnation Creek Coho are used as the wild indicator population for west coast Vancouver Island Coho. Tanasichuk (2002) reported that *T. spinifera* biomass variations explained variations in Carnation Creek Coho return. This analysis was re-visited recently to include tests of the effects of spawner and smolt abundance, and also to use a new measure of return. The effect of *T. spinifera* persisted and currently explains 68% of the variation in return. Figure 6 compares observed and predicted values, and provides the forecasted return for 2010 based on *T. spinifera* biomass in 2009.

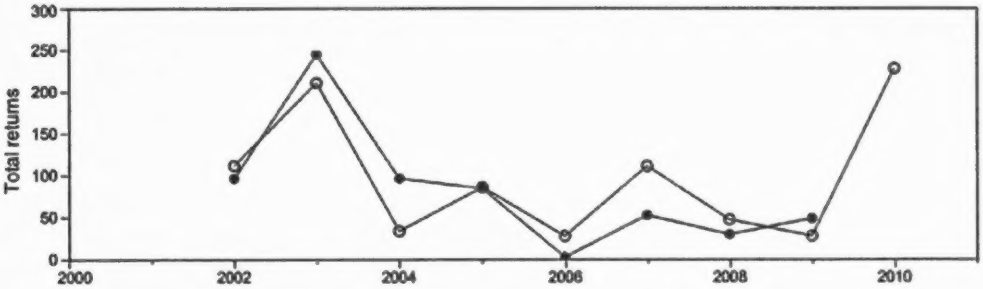


Figure 6. Observed (closed circles) and predicted (open circles) return of Carnation Creek Coho. Predicted values are estimated from the regression analysis.

Somass River Sockeye

Somass River Sockeye are an indicator stock for Barkley Sound Sockeye. Somass River Sockeye spawn in Great Central and Sproat lakes, which drain into the Somass River, which in turn flows into the head of the Alberni Canal. The majority of these fish return after spending two or three summers at sea. Sampling in May was inconsistent until 1998 so analyses including both age groups began in with the 2001 return year. Results of analyses by lake and marine age type showed that an average of 80% of return variability was explained solely by *T. spinifera* biomass.

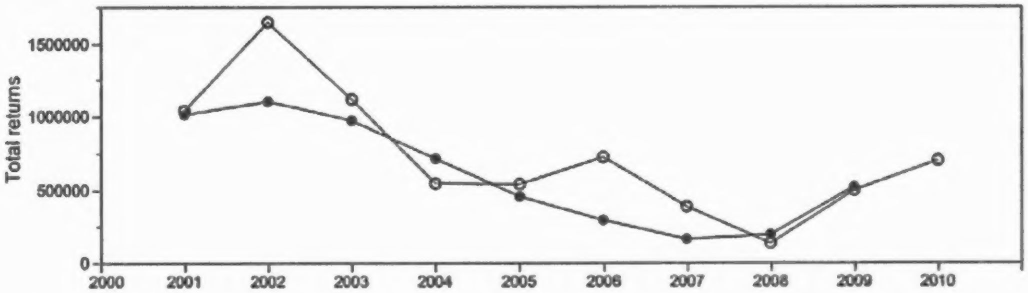


Figure 7. Observed (closed circles) and predicted (open circles) return of Somass River Sockeye. Predicted values are estimated from the regression analysis.

Anticipated consequences of 2009 prey and predator biomass levels

- **WCVI Herring**. Recruitment may increase in 2010 because of a reduction in hake biomass as of 2006 (this may be tempered somewhat for WCVI because of their specific requirements of *T. spinifera* prey biomass); higher *T. spinifera* prey biomass in 2009 should not result in improved growth because growth is a function of *T. spinifera* biomass during several years in the pre-recruit life history; adult survival rates in 2009 should increase because of higher *T. spinifera* biomass;
- **WCVI wild coho**. Marine survival may increase to about 10%, for the 2010 return year because of increased *T. spinifera* prey biomass in the 2009 smolt year;
- **Barkley Sound**. Returns in 2010 may increase from 2009 because of higher *T. spinifera* prey biomass in the 2007 and 2008 smolt years, and will begin to decline after 2010 because of lower prey biomass in 2009.

References

Fleischer, G. W., K.D. Cooke, P.H. Ressler, R.E. Thomas, S.K. de Blois, L.C. Hufnagle, A.R. Kronlund, J.A. Holmes, C.D. and Wilson. 2005. The 2003 integrated acoustic and trawl survey of Pacific hake, *Merluccius productus*, in U. S. and Canadian waters off the Pacific Coast. *NOAA Tech. Memo. NMFS-NWFSC-65.* 61p.

Tanasichuk, R. W. 1998. Interannual variations in the population biology and productivity of the euphausiid *Thysanoessa spinifera* in Barkley Sound, Canada, with special reference to the 1992 and 1993 warm ocean years. *Mar. Ecol. Prog. Ser.* 173: 163-180.

Tanasichuk, R. W. 1999. Interannual variation in the availability and utilization of euphausiids as prey for Pacific hake (*Merluccius productus*) along the southwest coast of Vancouver Island. *Fish. Oceano.* 8: 150-156.

Tanasichuk, R. W. 2002. Implications of interannual variability in euphausiid population biology for fish production along the southwest coast of Vancouver Island: a synthesis. *Fish. Oceanogr.* 11: 18-30.

Tanasichuk, R. W. In press. An investigation of the biological basis of recruitment variability of British Columbian populations of Pacific herring (*Clupea pallasi*). *Fish. Oceano.*

Tanasichuk, R. W. and R. Routledge. In press. An investigation of the biological basis of return variability for sockeye salmon (*Oncorhynchus nerka*) from Great Central and Sproat lakes, Vancouver Island. *Fisheries Oceanography.*

Tanasichuk, R. W. Submitted. An investigation of the biological basis of variation in age-specific survival rates of adult Pacific herring (*Clupea pallasi*) from British Columbia. *Fish. Oceano.*

Tanasichuk, R. W., D. M. Ware, W. Shaw and G. A. McFarlane. (1991) Variations in diet, daily ration and feeding periodicity of Pacific hake (*Merluccius productus*) and spiny dogfish (*Squalus acanthias*) off the lower west coast of Vancouver Island. *Can. J. Fish. Aquat. Sci.* 48: 2118-2128.

SEABIRD BREEDING ON TRIANGLE ISLAND IN 2009: EARLY AND SUCCESSFUL

Mark Hipfner, Environment Canada

Triangle Island Background and Species Natural History

Marine birds can be effective indicators of the state of marine ecosystems because they gather in large and highly visible aggregations to breed and because, as a group, they feed at a variety of trophic levels (zooplankton to fish). Seabird breeding success is closely tied to the availability of key prey species, and as a result, can vary widely among years, depending on ocean conditions. Triangle Island (50°52' N, 129°05' W) in the Scott Island chain off northern Vancouver Island, supports the largest and most diverse seabird colony along the coast of British Columbia. Since 1994, researchers from the Centre For Wildlife Ecology (a partnership between Environment Canada and Simon Fraser University), have visited Triangle Island to collect annual time-series information on seabird demography and ecology. This report presents key indicators of seabird breeding at Triangle Island in 2009, and places 2009 results within the context of the 1994-2008 time series.

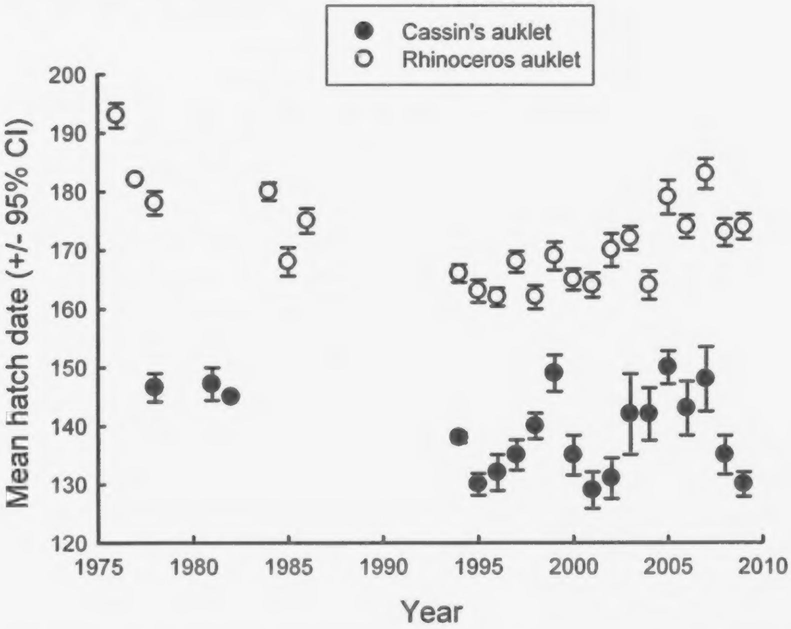


Figure 1. Timing of breeding for two focal seabirds, zooplanktivorous Cassin's auklet and more piscivorous Rhinoceros auklet, on Triangle Island, British Columbia, 1976-2009. Breeding in 2009 was early for Cassin's auklets, and near long-term averages for Rhinoceros auklets.

Timing of breeding

Variation in the timing of avian breeding is determined primarily by female condition prior to and during the period of egg formation, which is itself related to food availability early in the season. Over the last 15 years, Cassin's auklets in general have tended to lay eggs earlier in cold-water years and to breed more successfully as a result. Note that hatching occurred relatively early in 2009, similar to 2008 and 2000-2002 period (Fig. 1). For Rhinoceros auklets, timing of breeding in general has continued to revert back towards long-term averages in recent years (Fig. 1).

Breeding success

Cassin's auklets bred successfully in 2009, as expected from the cold spring SSTs and their early laying. In general, the auklets' offspring fledge at heavier masses in cold-water years, including 2009 (Fig. 2), because of strong temporal matching with important prey species. Diet data for Rhinoceros auklets in 2009 are unavailable at time of writing.

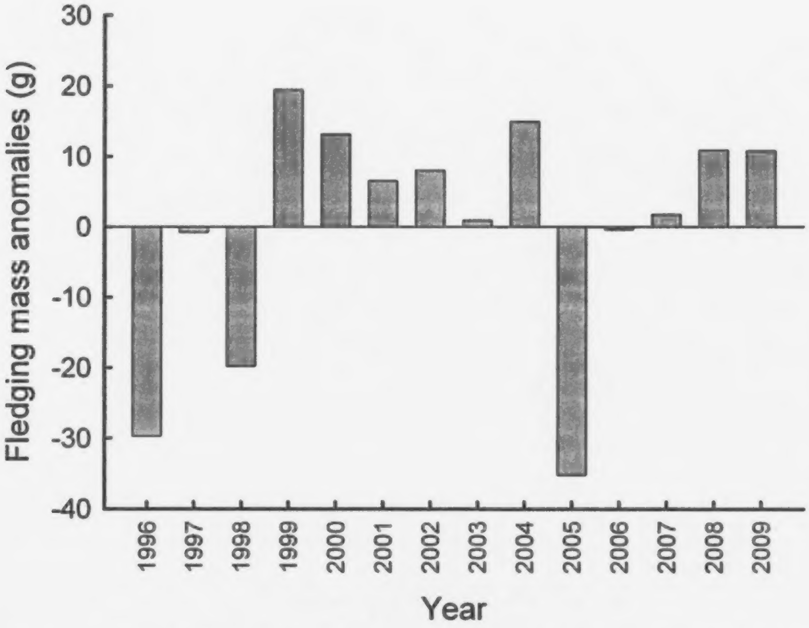


Figure 2. The mass of fledgling Cassin's auklet seabirds (when they leave the nest) are sampled annually by scientists of the Centre For Wildlife Ecology. Plotted above are anomalies of mass (relative to all years of observations) for Cassin's auklet chicks.

Links Scott Islands Marine Wildlife Area (http://www.cpawsbc.org/pdfs/scott_islands_mwa.pdf)

Canadian Wildlife Service bird monitoring in BC (http://www.ecoinfo.ec.gc.ca/env_ind/region/seabird/seabird_data_e.cfm#Map)

Environment Canada Contact: Mark Hipfner (mark.hipfner@ec.gc.ca)

POPULATION TRENDS AND DRIVERS OF ANNUAL VARIABILITY IN SEABIRDS IN BARKLEY SOUND

Yuri Zharikov, Bob Hansen and Peter Clarkson
Resource Conservation, Pacific Rim National Park Reserve of Canada

We review the April-to-September marine abundance trends of the more common and regularly encountered species of seabirds in Barkley Sound and an adjacent coastal stretch between 1994 and 2009. At-sea surveys were conducted by staff of Pacific Rim National Park Reserve in 1994 - 1996 and 1999 – 2009 along three transects – two in the Broken Group Islands and one further south along the West Coast Trail (BGI-Inner, BGI-Outer, and WCT, Figure 1). Over 35 species of seabirds have been recorded during the monitoring program.

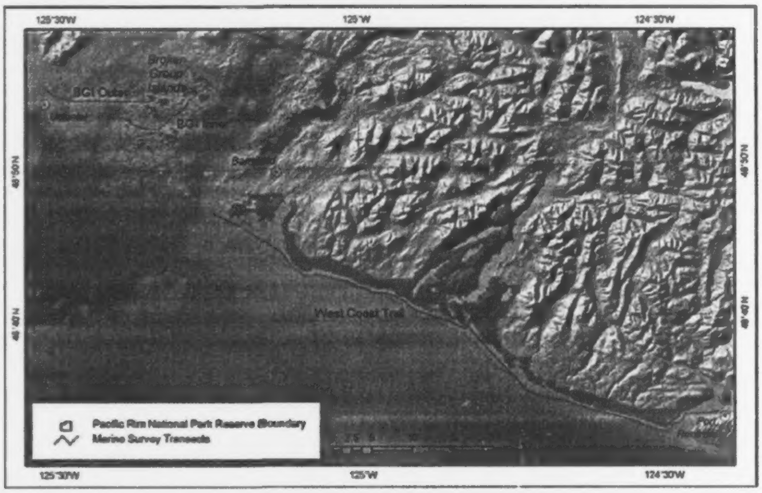


Figure 1. At-sea seabird transects in the waters of Pacific Rim National Park Reserve of Canada.

Of the species or groups of species monitored in this study between 1994-2009, three species declined considerably: common murre (*Uria aalge*) by 81%, Rhinoceros auklet (*Cerorhinca monocerata*) by 74%, and marbled murrelet (*Brachyramphus marmoratus*) by 65%. Three species of scoters (black *Melanitta nigra*, surf *M. perspicillata* and white-winged *M. fusca* combined) declined noticeably by 43%. Pigeon guillemot (*Cepphus columba*) and cormorants (pelagic *Phalacrocorax pelagicus* and Brandt's *Ph. penicillatus* combined) displayed only minor declines at 7% and 8% respectively. Two phalarope species (red *Phalaropus fulicarius* and red-necked *Ph. lobatus* combined) were the only ones to display a clear increase (76%) over the study period. Although we found divergent population trends in the species or groups of seabird species monitored in Pacific Rim, several common patterns are noted below.

The three species noted above that have declined considerably over the past 15 years are piscivorous, and are part of a coast-wide phenomenon from California and Alaska, and their decline suggests major degradation of food base for these birds that my be affected by both increased climate variability (Hedd et al. 2006; Lee et al. 2007; Irons et al. 2008) and pressure on fish stocks from commercial fisheries (Hawkins et al. 2003; Frederiksen et al. 2004). Increased climate variability and warmer coastal water seem to reduce abundances of "northern" species of zooplankton (see Mackas et al.2007, and in this report) and abundance of some larval and juvenile fish (Nagasawa 2001, Trudel, this report), which results in poor reproductive success for seabirds and reduced recruitment (Hedd et al. 2006; Lee et al. 2007).

SPECIES	Annual Trend	Ocean Productivity	Ocean Climate – Local	Ocean Climate - Regional
Marbled Murrelet	NEGATIVE	POSITIVE	NS	SOI - Negative
Common Murre	NEGATIVE	POSITIVE	NS	NS
[illegible]	STABLE	NS	SST - Negative	PDO – Positive
[illegible]	STABLE	NS	SST – Positive	NS
[illegible]	STABLE	NEGATIVE	NS	SOI - Positive
Rhinoceros Auklet	NEGATIVE	POSITIVE	NS	NS
Pigeon Guillemot	STABLE	NS	SST - Negative	SOI - Negative
Albatrosses	POSITIVE	NS	NS	PDO – Negative
Scoters	NEGATIVE	NS	SST - Negative	NS

Table 1. Summary of seabird responses to potential population drivers, for those seabirds whose numbers have declined in the past 15 years with little recent recovery.

The major El Niño event of 1997-98 resulted in poor seabird reproductive success and recruitment along the entire west coast of North America (e.g. Hedd et al. 2006; Lee et al. 2007; Slater & Byrd 2009). In our data this impact and the impact of a series of smaller Los Niños in 2002-03, 2004-05, and 2006-07 is clearly seen in subsequent population declines in marbled murrelets, rhinoceros auklets, common murres, scoters and to some degree cormorants, and pigeon guillemots. Under these conditions local declines cannot be compensated by immigration from elsewhere.

Most species (except for the common murre) responded positively to the cooler local oceanic conditions observed in 2007 and 2008. Cooler coastal waters in BC are generally thought to result in increased energy flows through phyto- and zooplankton (Mackas et al. 2007 and this report) to juvenile fish (Trudel, this report) to seabirds. In the case of auklets on Triangle Island in northern B.C., their chicks generally fledge at higher weight in cool springs, associated with better nearby prey (Hipfner, this report). Although the positive effects of cooler waters in 2007 to 2009 may have helped seabirds in Pacific Rim recently, local temperatures in early 2010 warmed quickly in association with El Niño of this winter.

The connection between local bird abundance and oceanic conditions is also seen in black oystercatchers (*Haematopus bachmani*) and glaucous-wing gulls (*Larus glaucescens*), with cooler years typically associated with higher breeding abundance. In 2009 relative to 2008 the monitored Pacific Rim population of black oystercatchers experienced 9.4% increase in the number of nests, 10.3% increase in the number of birds and 10.9% increase in productivity. On a site-by-site basis, the number of nests remained the same at 14 nesting sites, decreased at 2 sites and increased at 7 sites between the two years. Systematic historic data do not exist for all 23 sites currently monitored in the park. However for two of the sites, Florencia Island and Seabird Rocks, the data series are available. Both sites supported relatively large populations of black oystercatchers in the late 1980s. Their numbers declined in the mid- to late-1990s when local ocean waters were warm. In the early 2000s breeding numbers at both locations were low, but there has been a steady increase in the breeding population at these two index sites over the past 9 years.

The year 2009 was also more favourable for gull breeding than in 2008. The average reproductive index (number of eggs and/or chicks per nest) was 1.6 in 2008 and 1.9 in 2009 (Florencia colony only), which is a 19% increase. In 2008 27% of adult birds present at the colonies did not breed. In 2009 this proportion was only 12%. The proportion of 3-egg or 3-chick nests, the maximum average number per nest, was 0.30 in 2008 and 0.41 in 2009. This means that the adults were on average in better physical shape, which allowed them to breed at a higher frequency and produce larger clutches and broods. Lots of sardine remnants were found at gull colonies in the park in 2009 which the birds would have brought to feed their chicks. This observation meshes well with reports from tour and fishing boat operators working in the waters of and adjacent to the park. Thus food was abundant for the birds in 2009.

Assessing the overall trend in the gull population at Pacific Rim it appears that the two smaller colonies on While Island and Sea-lion Rocks remained stable over the past 40 years. The colonies on Seabird Rock and Florencia have experienced sharp declines in the early 70s, which followed a major collapse of herring stocks. Gull numbers at these two colonies remained stable through the 80s and 90s. The recent trend, however, at least on Florencia, has been a steep build-up of numbers towards the levels seen in late 1960—early 70s, likely represents locally improving foraging conditions, which improve breeding success and survival.

References

Frederiksen M, S. Wanless, M.P. Harris, P. Rothery and L.J. Wilson. 2004. The role of industrial fisheries and oceanographic change in the decline of North Sea black-legged kittiwakes. *Journal of Applied Ecology* 41: 1129-1139.

Hawkins S.J., A.J. Southward and M.J. Genner 2003. Detection of environmental change in a marine ecosystem – evidence from the western English Channel. *The Science of the Total Environment* 310: 245–256.

Hedd A., D.F. Bertram, J.L. Ryder and I.L. Jones. 2006. Effects of interdecadal climate variability on marine trophic interactions: rhinoceros auklets and their fish prey. *Marine Ecology Progress Series* 309: 263-278.

Irons D.B., T. Anker-Nilssen, A.J. Gaston , V.G. Byrd , F. Knud , G. Gilchrist , M. Hario , M. Hjernquist , Y.V. Krasnov , A. Mosbech , B. Olsen , A. Petersen , J.B. Reid , G.J. Robertson, H. Strøm , and K.D. Wohl. 2008. Fluctuations in circumpolar seabird populations linked to climate oscillations. *Global Change Biology* 14: 1455-1463.

Lee DE, N. Nur and W.J. Sydeman. 2007. Climate and demography of the planktivorous Cassin's auklet *Ptychoramphus aleuticus* off northern California: implications for population change. *Journal of Animal Ecology* 76: 337-347.

Mackas, D.L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warming ocean: recent evidence from the North Pacific. *Progress in Oceanog*raphy 75: 223-252.

Nagasawa K. 2001. Long-term variations in abundance of Pacific herring (Clupea pallasi) in Hokkaido and Sakhalin related to changes in environmental conditions. *Progress in Oceanography* 49: 551-564.

Slater L., G.V. Byrd. 2009. Status, trends, and patterns of covariation of breeding seabirds at St Lazaria Island, Southeast Alaska, 1994-2006. *Journal of Biogeography* 36: 465-475.

EFFECTS OF CLIMATE CHANGE ON AQUATIC INVASIVE SPECIES IN BRITISH COLUMBIA

Veronica Lo[1], Kai M.A. Chan[2], Colin D. Levings[3]
[1]Canadian Parks and Wilderness Society, [2]Institute for Resources, Environment and Sustainability, University of British Columbia, [3]Fisheries and Oceans Canada

Invasive species are introduced species that have a negative impact on ecosystem function and may cause economic damage or impacts to human health (Carlton 2002). A growing body of literature demonstrates that global climate change may create new introduction pathways for aquatic invasive species (AIS), and enhance AIS establishment and spread. Climate change is also predicted to cause marine species to expand or shift their ranges poleward (Cheung et al. 2009, Harley et al. 2006). Here, we briefly review the effects of climate change on AIS and species range shifts and expansions that may have implications for marine and coastal ecosystems in British Columbia.

New introduction pathways caused by global climate change

Current vectors of aquatic invasive species (AIS) include commercial shipping, recreational boating, the aquarium and live bait trades, aquaculture, and canal/dam construction. Climate change might add to the increased introduction pathways from global trade, for example, through increased flooding events and new opportunities for aquaculture facilities or water gardens for warm water species (Rahel and Olden 2008). Model projections show that Arctic sea ice, which currently prevents ship passage, could melt at a rate that would open new shipping routes in the next few decades (Kerr 2002, Stroeve et al. 2007). New shipping pathways, combined with new connections between ports and reduced transit times (thus increasing the survival of ballast-water and biofouling organisms), will likely increase introduction rates of AIS (Pyke et al. 2008, Reid et al. 2007).

Climate change challenges our notion of 'introduction' at the heart of definitions of AIS: it creates a new category of human-induced introductions that are results of human activity (greenhouse gas emissions), but indirectly because they may move on their own accord. While these species merit different management approaches (because there is no active transport step associated with human activity), they merit equal concern, for several reasons. First, their presence is still attributable to human-caused changes. Second, the ecological consequences of such climate-opportunists are likely to be similar to those of human-transported species (Sorte et al. 2010). Finally, it will be increasingly difficult to distinguish climate change-mediated introductions from climate-induced range changes (Walthur et al. 2009).

Facilitation of AIS establishment success

The establishment success of introduced species is limited in part by their ability to withstand the physical and biological characteristics of their new environment. Climate change will lower these barriers in some areas by raising minimum cold temperatures that currently impede AIS survival (Rahel and Olden 2008). Competition and predation by AIS on native species may also be enhanced by climate change, as might diseased virulence (Rahel and Olden 2008). Altered precipitation patterns may change estuarine salinity dynamics, allowing survival of species with broad salinity tolerances (Carlton 2000). At the same time, climate change is not likely to decrease the impact of current invasive species, as many are already tolerant to a wide range of environmental conditions (Qian and Ricklefs 2006). Examples of how climate change can facilitate establishment success include the following:

- The invasive **golden star tunicate** (*Botryllus schlosseri*) and **violet tunicate** (*Botrylloides violaceus*) are currently established on the east and west coasts of Vancouver Island, but data on their temperature and salinity tolerances indicate that both species are able to inhabit most areas of the B.C. coast (Epelbaum et al. 2009). In New England, non-native tunicates recruited earlier than native species in years when winter water temperatures were warmer, and grew faster at higher temperatures, such that communities may become dominated by these non-native species (Stachowicz et al. 2002).
- Larvae of the non-native **varnish clam** (*Nuttallia obscurata*), a relatively recent invader in B.C. waters, have a wide range of salinity and temperature tolerances, but experience optimal growth at warmer temperatures and higher salinities (Dudas and Dower 2006). Varnish clams have higher fecundity and reach sexual maturity earlier than other co-occurring bivalves, which may provide an advantage over native species (Dudas and Dower 2006).
- Increased seawater temperatures may create favourable conditions for parasites, such as the **sea lice** *Lepeophtheirus salmonis*, which has higher survival and faster maturity at warmer temperatures (Johannessen and Macdonald 2009).
- Native seagrass species may be vulnerable from interactions with new species and heat stress, as they cannot extend their ranges as quickly as animals with planktonic larvae (Williams 2007). Climate change may affect the zonation patterns of the non-native **seagrass** *Zostera japonica* along its southern range on the Pacific coast of North America. *Z. japonica* will be at a higher risk of dessication at the upper intertidal zones due to higher air temperatures in the future, possibly resulting in a shift to the lower intertidal zones. This in turn could lead to increased competition with the native seagrass *Zostera marina*, which typically occupies the lower intertidal to upper subtidal zones (Shafer et al. 2008).
- The Chinese **mitten crab** (*Eriocheir sinensis*), now established throughout parts of North America and Europe, requires a salinity of >15 in order to reproduce (Herborg et al. 2007). This limitation to their dispersal ability may be removed as salinity changes occur in parts of the coast as a result of climate change (Rahel and Olden 2008).
- Harmful algal blooms may increase in occurrence if phytoblankton bloom compositions,, which are very sensitive to water temperature changes, are altered (Johannessen and Macdonald 2009).
- The risk of establishment of AIS into estuaries by ballast water may be amplified because many known AIS are tolerant to large changes in temperature and salinity (Levings et al. 2004).
- Over the last two decades, an increase in abundance and accelerated spread of the invasive **cordgrass** *Spartina anglica* (also established in B.C.) was observed in the European Wadden Sea, possibly promoted by warmer spring temperatures (Nehring and Hesse 2008).

Facilitation of AIS spread and species range expansions

Climate change may increase the duration of occurrences of initial AIS introductions, increasing the frequency of introductions or enlarging the range and area of suitable habits. As a result, species will be more likely to persist and develop larger populations over increasing spatial ranges (Walthur et al. 2009). Examples of these effects include the following:

- The **European green crab** (*Carcinas maenas*) has traveled north from San Francisco Bay to the west coast of Vancouver Island, and it may expand its range to northern B.C. and Alaska (Gillespie et al. 2007).
- Two species of **non-native tunicates**, *Styela clava* and *Molgula manhattensis*, have expanded their ranges northward on the Pacific coast in the last 20-50 years, concurrent with increased water temperatures (Carlton 2002).
- The historical range of the **Humboldt squid** (*Dosidicus gigas*) extends along the subtropical coasts of North and South America (Zeidberg and Robison 2007), In recent years it has appeared further north along the west coast of North America (Crawford and Irvine 2009), coincident with significant declines in Pacific hake (*Merluccius productus*) populations (Zeidberg and Robison 2007). Large numbers of Humboldt squid washed up on beaches in Tofino on several occasions last summer (2009) (Gillespie, this report).
- Data on intertidal invertebrate assemblages in California over a 60-year time period indicate that southern invertebrate species increased in abundance and expanded their ranges as water temperatures increased, while northern species that were not tolerant of the warmer conditions declined (Barry et al. 1995).
- Climate-related range expansions of the **limpet** *Tectura depicta* in California has affected populations of the native seagrass *Zostera marina* (Zimmerman et al. 2001).
- In California, the invasive **blue mussel** *Mytilus galloprovincialis* (also present on the B.C. coast) has a higher tolerance for warmer temperatures and increased salinity levels than the native blue mussel, indicating its range may expand northward (Braby and Somero 2006).

Global data suggests increases in atmospheric carbon dioxide, ocean temperatures, sea level, and increased frequency and intensity of severe weather events. These impacts are projected to continue in the future (IPPC 2007). Ocean temperatures measured over many decades at shorestations in British Columbia indicate that warming is indeed happening in B.C. waters (Beamish et al. 2009, Chandler, this report), consistent with global trends. It is thus imperative to identify the vulnerabilities of species and ecosystems to the impacts of AIS establishment, which may be magnified by climate change and increased global trade in the future.

We have summarized some of the ways in which climate change can affect AIS in B.C. waters: by increasing introduction pathways, facilitating AIS establishment success, and promoting species range expansions. However, climate change stresses on coastal and marine ecosystems will likely not act in isolation, highlighting the need to consider how other interacting and possibly synergistic factors, such as pollution, habitat loss, over-fishing, and biodiversity loss, will affect invasion dynamics in B.C.

References

Barry, J.P., C.H. Baxter, R.D. Sagarin and S.E. Gilman (1995) Climate-related, long-term faunal changes in a California rocky intertidal community. *Science* 267(5198): 672-675.

Beamish, R.J., J.R. King and G.A. McFarlane (2009) Pp 14-55 in R.J. Beamish (Ed) *Impacts of climate and climate change on the key species in the fisheries in the North Pacific*. PICES Scientific Report No. 35R. PICES Working Group on Climate Change, Shifts in Fish Populations, and Fisheries Management. North Pacific Marine Science Organization (PICES), Secretariat, Sidney BC, Canada, 217 pp.

Braby, C.E. and G.N. Somero (2006) Following the heart: temperature and salinity effects on heart rate in native and invasive species of blue mussels (genus *Mytilus*). *Journal of Experimental Biology* 209(13): 2554–2566.

Carlton, J.T. (2002) Global change and biological invasions in the oceans. Pages 31-53 in Mooney H.A. and R.J. Hobbs (Eds), *Invasive Species in a Changing World*. Island Press, Washington, 480 pp.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson and D. Pauly (2009) Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 10: 235-251.

Crawford, W.R. and J.R. Irvine (2009) *State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems*. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi + 121 p.

Dudas, S.E. and J.F. Dower (2006) Reproductive ecology and dispersal potential of varnish clam *Nuttalia obscurata*, a recent invader in the northeast Pacific Ocean. *Marine Ecology Progress Series* 320: 195-205.

Epelbaum, A., L. Herborg, T.W. Therriault and C.M. Pearce (2009) Temperature and salinity effects on growth, survival, reproduction, and potential distribution of two non-indigenous botryllid ascidians in British Columbia. *Journal of Experimental Marine Biology and Ecology* 369: 43-52.

Gillespie, G.E., A.C. Phillips, D.L. Paltzat and T.W. Therriault (2007) Status of the European green crab, *Carcinus maenas*, in British Columbia - 2006. *Can. Tech. Rep. Fish. Aquat. Sci.* 2700: vii + 39 p.

Harley, C.D.G., A.R. Hughes, K.M. Hultgren, B.G. Miner, C.J.B. Sorte, S.C. Thornber, L.F. Rodriguez, L. Tomanek, and S.L. Williams (2006) The impacts of climate change in coastal marine systems. *Ecology Letters* 9: 228-241.

Herborg, L.M., C.L. Jerde, G.M. Lodge, G.M. Ruiz and H.J. MacIsaac (2007) Predicting invasion risk using measures of introduction effort and environmental niche models. *Ecological Applications* 17(3): 663-674.

IPCC (2007) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, R.K. Pachauri and A. Reisinger (eds.)). IPCC, Geneva, Switzerland, 104 pp.

Johannessen, S.C. and R.W. Macdonald (2009) Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada. *Climate Research* 40: 1-21.

Kerr, R.A. (2002) A warmer Arctic means change for all. *Science* 297: 1490–1493.

Levings, C.D., J.R. Cordell, S. Ong and G.E. Piercey (2004) The origin and identity of invertebrate organisms being transported to Canada's Pacific coast by ballast water. *Canadian Journal of Fisheries and Aquatic Sciences* 61:1-11.

Pyke, C.R., R. Thomas, R.D. Porter, J.J. Hellmann, J.S. Dukes, D.M. Lodge and G. Chavarria (2008) Current practices and future opportunities for policy on climate change and invasive species. *Conservation Biology* 22(3): 585-592.

Qian. H., and R.E. Ricklefs (2006) The role of exotic species in homogenizing the North American flora. *Ecology Letters* 9: 1293-1298.

Rahel, F.J. and J.D. Olden (2008) Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* 22(3): 521-533.

Reid, P.C., D.G. Johns, M. Edwards, M. Starr, M. Poulins and P. Snoeijs (2007) A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom *Neodenticula seminae* in the North Atlantic for the first time in 800,000 years. *Global Change Biology* 13(9): 1910-1921.

Shafer, D.J., S. Wyllie-Echeverria and T.D. Sherman (2008) The potential role of climate in the distribution and zonation of the introduced seagrass *Zostera japonica* in North America. *Aquatic Botany* 89: 297-302.

Sorte, C.J.B., S.L. Williams and J.T. Carlton (2010) Marine range shifts and species introductions: comparative spread rates and community impacts. *Global Ecology and Biogeography* 19: 303-316.

Stachowicz, J.J., J.R. Terwin and R.B. Whitlatch (2002) Linking climate change and biological invasions: ocean warming facilitates nonindigenous species invasions. *Proceedings of the National Academy of Sciences USA* 99(24):15497–15500.

Stroeve, J., M. Holland, W. Meier, T. Scambos and M. Serreze (2007) Arctic sea ice decline: faster than forecast. *Geophysical Research Letters* 34:L09501.

Walthur, G.R., A. Rocques, P.E. Hulme, M.T. Sykes, P. Pyšek, I. Kühn, M. Zobel, S. Bacher, Z. Botta-Dukat, H. Bugmann, B. Czúcz, J. Dauber, T. Hickler, V. Jarošík, M. Kenis, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko, W. Solarz, W. Thuiller, M. Vilà, K. Vohland and J. Settele (2009) Alien species in a warmer world: risks and opportunities. *Trends in Ecology and Evolution* 24(12): 686-693.

Williams, S. (2007) Introduced species in seagrass ecosystems: Status and concerns. *Journal of Experimental Marine Biology and Ecology* 350: 89-110.

Zeidberg, L.D. and B.H. Robison (2007) Invasive range expansion by the Humboldt squid, Dosidicus gigas, in the eastern North Pacific. *Proceedings of the National Academy of Sciences USA* 104:12948–12950.

Zimmerman R.C., D. Korhs and R. Alberte (1996) Top-down impact through a bottom-up mechanism: the effect of limpet grazing on growth, productivity and carbon allocation of *Zostera marina*. *Oecologia* 107: 560–567.

SMALL PELAGIC FISHES

Jake Schweigert and Jaclyn Cleary, Fisheries and Oceans Canada

The report focuses on Pacific herring and sardine for which ongoing data collection and monitoring occurs. An egg and larval survey continues for eulachon within the Fraser River and indicates that this population remains at critically reduced abundance.

West Coast of Vancouver Island

Abundance of the West Coast Vancouver Island herring stock decreased from 1977 through to the present to levels not seen since the late 1960s. Abundance in 2009 was similar to low levels observed since 2006 and remained well below the fishery threshold. Warm ocean temperatures in 2003 to 2006 appear to be associated with poor recruitment for these herring (the opposite of herring stocks in the Strait of Georgia), and an increase in summer biomass of predators.

Sardine returned to southern Vancouver Island waters in 1992 after a 45 year absence, and expanded their distribution northward throughout the west coast of Vancouver Island, Hecate Strait and Dixon Entrance by 1998. In 2009 sardines appeared in Canadian waters by mid-June. The distribution differed from that in 2006 and 2008, with stock concentrated inshore and in the inlets of the west coast of Vancouver Island. Sardine schools also extended northwards into southern Hecate Strait and Queen Charlotte Sound. The exceptionally strong 2003 year-class continues to be the predominant component in the widespread distribution of large sardines throughout the area.

North Coast

Exploitable herring biomass in the PNCIMA region (central and northern BC coastal waters) represents a combination of migratory stocks from the Queen Charlotte Islands, Prince Rupert and Central Coast areas. Recruitment in the Queen Charlotte Islands stock has been reduced for the past decade, resulting in low abundance, while recruitment in the Prince Rupert and Central Coast stocks had been generally good, because of sporadic strong year classes. However, two of the most recent year-classes (2003 and 2005) have been weak in these areas resulting in declines in abundance from the previous year. The 2006 year-class was above average in the Queen Charlotte Islands and the Central Coast resulting in slight increases in abundance for these areas.

Small pelagic fishes: detailed analyses

Herring off the west coast of Vancouver Island

Since about 1977, the recruitment of herring off the west coast of Vancouver Island has been generally poor, interspersed with a few good year-classes. As a result, the productivity of the west coast of Vancouver Island herring stock has been declining since the early 1980s (Figure 1). Research studies have shown that herring recruitment in this region tends to be negatively correlated with increasing temperatures probably reflecting: 1) poor feeding conditions for herring larvae and juveniles during their first growing season; and 2) a general increase in the mortality rate of the larvae and juveniles due to an increase in the intensity of invertebrate and fish predation in the rearing area in warm years. Studies investigating predation rates confirm that the negative correlation between herring recruitment and hake biomass could be caused by predation or competition for food. Ocean conditions were warmer in 2002 to 2005, impacting herring survival, resulting in reduced biomass and recruitment. However, cooler conditions in 2006 and declining hake abundance should improve herring survival in the short term.

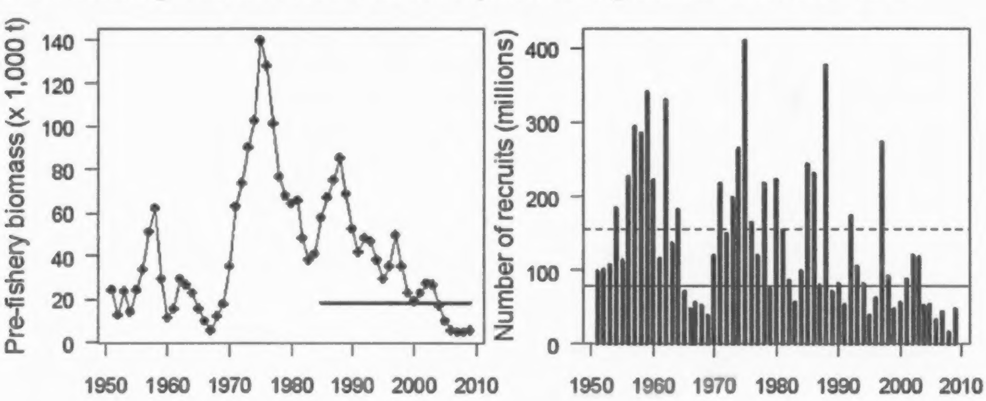


Figure 1. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the West Coast Vancouver Island herring stock. Left figure: solid horizontal line denotes commercial fishing cutoff. Right figure: boundary for 'poor'- 'average' recruitment indicated by solid line; boundary for 'average'- 'good' recruitment indicated by dashed line. Note that 7 of the last 10 recruitments have been 'poor'.

Pacific Sardine off the west coast of Vancouver Island

Pacific sardine is a migratory species, annually moving between spawning grounds in southern California to the rich feeding areas off the west coast of Vancouver Island. The sardine fishery in Canadian waters collapsed in 1947 and by the early 1950s off California due to unfavourable environmental conditions.

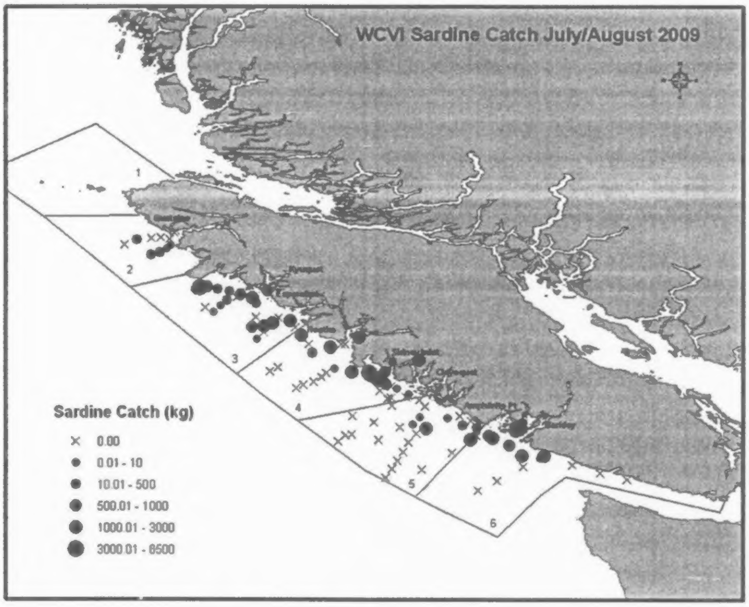


Figure 2. Distribution of Pacific sardine in BC waters during 2009 based on the sardine trawl survey.

After a 45-year absence from British Columbia waters, sardines reappeared off the west coast of Vancouver Island in 1992. From 1992-1996, their distribution was limited to the south-western portion of Vancouver Island. In 1997, their distribution expanded northward and by 1998 sardines inhabited waters east of the Queen Charlotte Islands throughout Hecate Strait and up to Dixon Entrance. Sardine distribution again contracted southward in 1999 during La Niña. During 2006 and 2008, sardines appeared in Canadian waters in late-June and were distributed offshore and largely north of Vancouver Island into southern Hecate Strait and Queen Charlotte Sound. In 2009, sardine were widely distributed along the west coast of Vancouver Island but concentrated inshore (Figure 2), relative to earlier years. The most recent U.S. assessment suggests that coast-wide abundance off Canada and the U.S. lower 48 states peaked in 2000 and has declined since, decreasing to about 700,000 tonnes in 2009 (Figure 3).

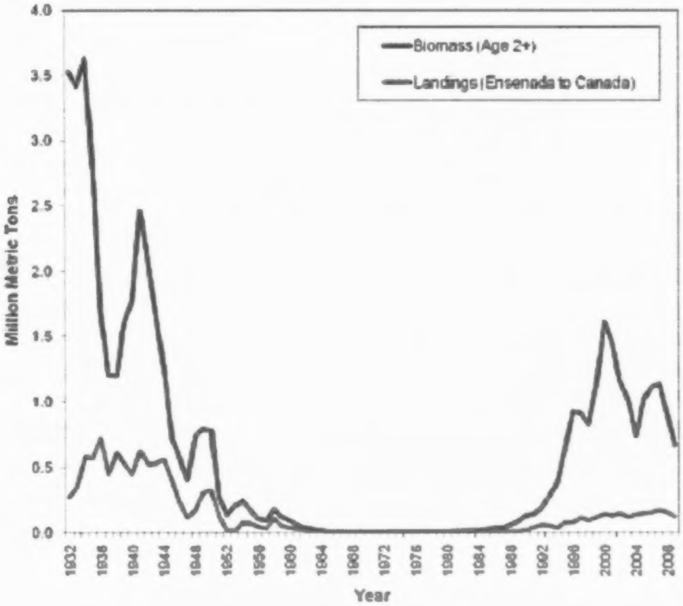


Figure 3. Time series of Pacific sardine stock biomass off Canada, USA, and Mexico (x1,000 tonnes) of age 2 and older fish, estimated from an age-structured stock assessment model (data from Hill et al. 2009). Landings include fish from Ensenada, Mexico to Canada.

Herring in Hecate Strait

The biomass of herring in the Hecate Strait area represents a combination of three major migratory stocks: the Queen Charlotte Islands stock, the Prince Rupert stock, and the Central Coast stock. Over the past decade, abundance in the Queen Charlotte Islands (Figure 4) has been depressed whereas abundance in both Prince Rupert and the Central Coast have remained stable (Figures 5-6). Recruitment to the Queen Charlotte Islands stock has been depressed with only 2 'good' year-classes out of the past 10 (Figure 4) while the Prince Rupert stock (Figure 5) has experienced a 'good' recruitment at least every 4 years since 1980. Recruitment to the Central Coast stock (Figure 6) has been less regular but the 'good' year-classes that have occurred were very strong. Indications are that the most recent recruitments (2003-2005 year-classes) are 'poor' or 'average', resulting in declines all three northern stocks. Cooler conditions in 2006 resulted in 'average' to 'good' recruitment in all three areas.

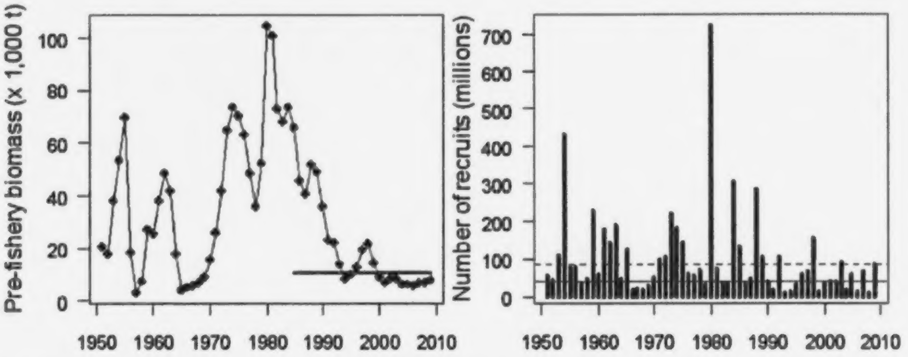


Figure 4. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Queen Charlotte Islands herring stock. Left figure: solid horizontal line denotes commercial fishing cutoff. Right figure: boundary for 'poor'- 'average' recruitment indicated by solid line; boundary for 'average'- 'good' recruitment indicated by dashed line. Note that 2 of the last 10 years have seen 'good' recruitment.

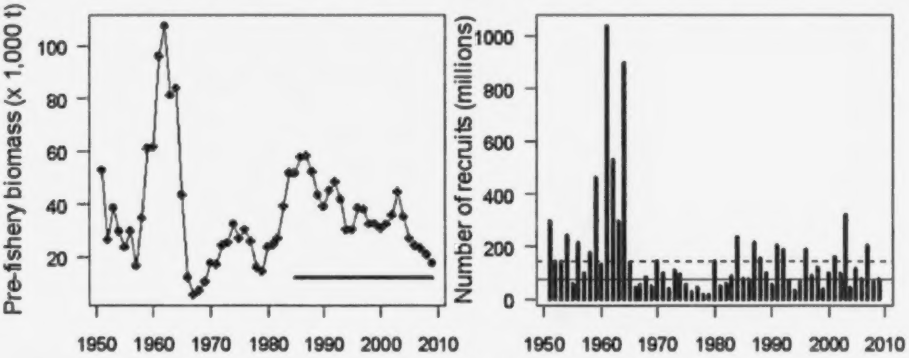


Figure 5. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Prince Rupert District herring stock. Left figure: solid horizontal line denotes commercial fishing cutoff. Right figure: boundary for 'poor'- 'average' recruitment indicated by solid line; boundary for 'average'- 'good' recruitment indicated by dashed line. Note that 'good' recruitments have occurred almost every four years since 1980.

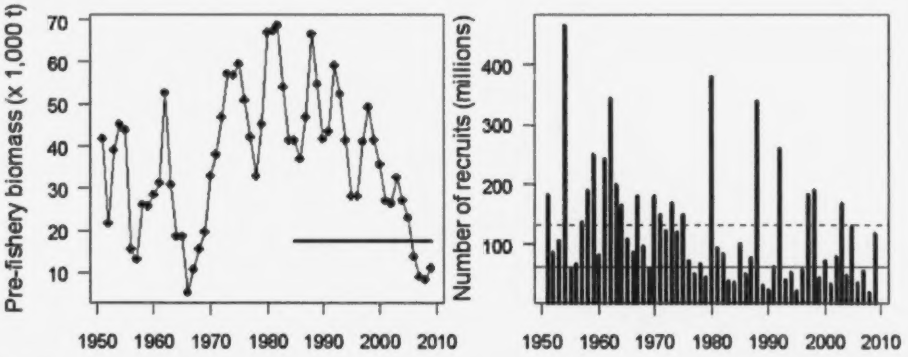


Figure 6. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Central Coast herring stock. Left figure: solid horizontal line denotes commercial fishing cutoff. Right

figure: boundary for 'poor'- 'average' recruitment indicated by solid line; boundary for 'average'- 'good' recruitment indicated by dashed line.

Small pelagic fishery interpretation and speculative results

West Coast Vancouver Island

Herring: Herring on the west coast of Vancouver Island are at historically low level and will remain so until ocean conditions change to increase stock productivity and/or reduce predation pressure..

Sardine: Sardines reappeared off the west coast of Vancouver Island in 1992. During the 1990s their distribution expanded northward from southern Vancouver Island through Hecate Strait to Dixon Entrance. In 2003 and 2004 the distribution of sardines in B.C. were limited to the inlets of Vancouver Island and offshore areas in the south. Warm conditions in 2002 to 2006 and a very strong 2003 year-class resulted in widespread distribution of sardines throughout southern Hecate Strait and Queen Charlotte Sound in 2006 through 2008. In 2009 sardine were again widely distributed into southern Hecate Strait but concentrated in inshore waters.

North Coast Major

Herring: Herring in the Hecate Strait area consist of migratory stocks from the Queen Charlotte Islands, Prince Rupert and Central coast areas. For the past decade, recruitment and abundance of the Queen Charlotte Islands stock has been low while recruitment and abundance of the Prince Rupert and Central Coast stocks have been stable. Recruitment of the 2003 and 2005 year-classes was weak in all three areas resulting in slight declines in all three areas in 2008. Cool conditions in 2006 resulted in improved recruitment and slight increases in abundance in all three areas. Declining hake abundance may result in improved herring recruitment in this area in the short term.

Reference

Hill, K.T., N.C.H. Lo, B. J. Macewicz, P. Crone and R. Felix-Uraga. 2009. Assessment of the Pacific sardine resource in 2009 for U.S. management in 2010. NOAA-TM-NMFS-SWFSC-452: 182p.

HUMBOLDT SQUID IN BRITISH COLUMBIA IN 2009

Graham Gillespie, Fisheries and Oceans Canada

The Humboldt squid, *Dosidicus gigas*, is a relatively recent addition to the fauna of British Columbia. The species normally ranged between California and Chile and was not recorded in British Columbia until the mid-1990s. At this time, Humboldt squid were observed on Station Papa surveys, but the species was not reported from nearshore waters. Despite exploratory fisheries for neon flying squid, *Ommastrephes bartrami*, in the late 1990s, Humboldt squid remained unknown or unreported (Gillespie 1997, Campagna et al. 2000). The first specimens of *D. gigas* from British Columbia were reported in 2004 when four specimens and a number of credible accounts were documented (Cosgrove and Sendall 2004). Humboldt squid returned in 2005 and again were reported in southeastern Alaska (Trudel et al. 2006). In 2007, Humboldt squid were reported in bycatch from coastal trawlers and a stranding of several adult squid was noted at Nootka Island (unpubl. data).

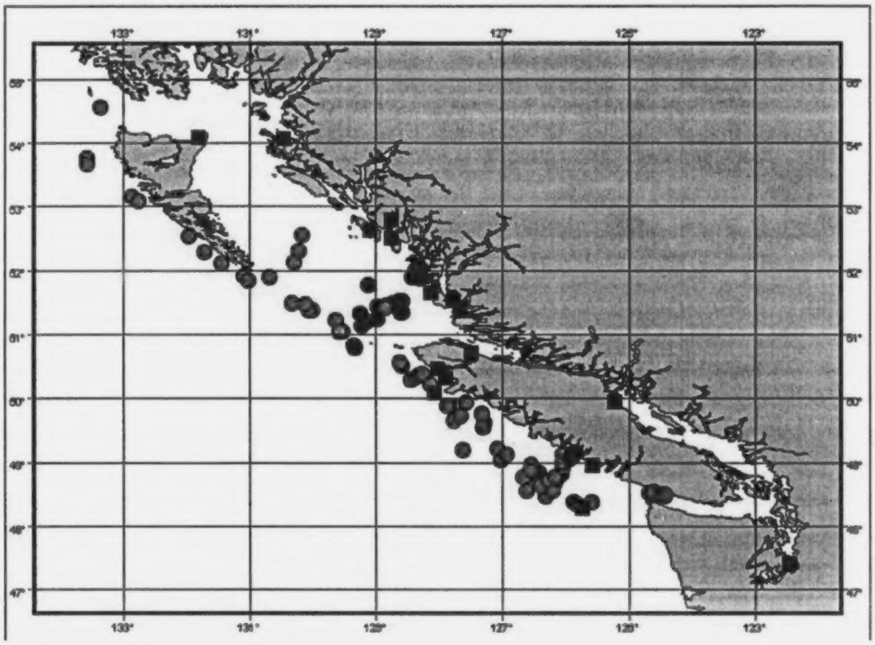


Figure 1. Records of Humboldt squid, Dosidicus gigas, *from British Columbia and Puget Sound in 2009 (blue squares are sightings, red squares are strandings, red circles are commercial bycatch and green circles are research catches).*

In 2009, Humboldt squid were widespread and abundant in British Columbia waters. They were recorded in both commercial and research catches from early July to October throughout British Columbia waters (Figure 1). They were very densely aggregated; a three-minute research tow yielded nearly 120 individuals and commercial bycatches were occasionally estimated in the tens of tons. In addition to catches and numerous sightings there were 10 significant stranding events reported throughout the exposed coast (Ucluelet to Massett) between August and October, as well as individuals washed onshore in Campbell River and Puget Sound in December.

Humboldt squid are seasonally-migrant, high-metabolism predators that can function as keystone predators in offshore and nearshore ecosystems. They prey primarily on pelagic species such as hake, myctophids, anchovies, sardines, pelagic rockfish and other squid (Field et al. 2007). Their diet could shift in northern waters depending on prey abundance, in particular depending upon the degree of overlap in time and space with salmon and herring.

Acknowledgements: Many people assisted in field collections, including Meggie Hudspith and Kent Tebbutt (Manchester University); and Kris Anderson, Karina Cooke, Ken Cooke, George Cronkite, Nora Crosby, Steve Romaine, Chelsea Stanley and Ted Sweeten (DFO). Particular thanks to John Lennic (F/V *OCEAN MAURADER*) for the loan of gear and advice.

References:

Campagna, S., G.E. Gillespie and W. Shaw. 2000. *Review of the 1997 and 1998 pilot commercial fisheries for neon flying squid (Ommastrephes bartrami) off the west coast of Canada.* Can. Ind. Rep. Fish. Aquat. Sci. 256. 74 p.

Cosgrove, J.A. and K.A. Sendall. 2004. *First records of Dosidicus gigas, the Humboldt squid in the temperate north-eastern Pacific.* Royal British Columbia Museum, Victoria. 10 p.

Field, J.C., K. Baltz, A.J. Phillips and W.A. Walker. 2007. *Range expansion and trophic interactions of the jumbo squid, Dosidicus gigas, in the California Current.* CalCOFI Rep. 48: 131-148.

Gillespie, G.E. 1997. Review of biology, fisheries and assessment of North Pacific oceanic squids, particularly *Ommastrephes bartrami*, *Onychoteuthis borealijaponica*, *Gonatopsis borealis* and *Berryteuthis magister*. Can. Stock Assess. Secretar. Res. Doc. 97/143. 40 p.

Trudel, M, G. Gillespie, J. Cosgrove and B. Wing. 2006. Warm water species in British Columbia and Alaska. p. 53. *In*: DFO. State of the Pacific Ocean 2005. DFO Sci. Ocean Status Report. 2006/001.

REDUCED CATCHES AND GROWTH RATES OF JUVENILE SALMON OFF THE WEST COAST OF VANCOUVER ISLAND IN 2009 COMPARED TO 2008

Marc Trudel, Mary Thiess, John Morris, Strahan Tucker, Tyler Zubkowski, and Yeongha Jung
Fisheries and Oceans Canada

Ocean surveys for juvenile salmon have been used to assess the distribution, growth, condition, and survival of Pacific salmon in different parts of the British Columbia coastal ecosystem since 1998. These surveys are usually conducted in late spring-early summer (June-July) and in the fall (October-November). In addition, juvenile salmon have been collected during winter (February-March) since 2001. This work assumes that marine survival will be higher in years when salmon are rapidly growing and are in good condition than in years of poor growth and condition. Hence, marine survival is expected to be positively correlated to indicators of juvenile salmon growth rate.

June-July catch-per-unit-effort (CPUE) of juvenile Chinook salmon, Sockeye salmon and Chum salmon declined off the west coast of Vancouver Island (WCVI) in 2009 relative to the previous year (Fig. 1). Although the CPUE of these species declined, they were within the average of their respective time series. Since the CPUE of these species were the highest on record in 2008, it is perhaps not surprising that their CPUE declined in 2009 (Fig. 1). In contrast, the CPUE of juvenile Coho salmon increased in June-July 2009 and was the highest on record off WCVI for this species (Fig. 1). Yet, growth rates of juvenile Coho salmon declined below the 1998-2008 average value both off WCVI and Southeast Alaska (Fig. 2). The lower growth rate observed in 2009 may be related to a shift in the zooplankton community from large lipid-rich copepods to small lipid-poor copepods (Mackas et al., this report). As our analyses indicate that the marine survival of WCVI salmon stocks is strongly correlated to the growth conditions for Coho salmon in this region (Trudel et al. 2008), the low juvenile Coho salmon growth suggest that marine survival will be average to below average for WCVI Coho salmon returning in 2010 relative to 1999-2009, as well as for WCVI Chinook salmon and Barkley Sound Sockeye salmon in 2011 relative to 2000-2009.

References:

Trudel, M., Thiess, M.E., Bucher, C., Farley, E.V., Jr., MacFarlane, B., Casillas, E., Morris, J.F.T., Murphy, J.M., and Welch. 2007. D.W. Regional variation in the marine growth and energy accumulation of juvenile Chinook salmon and coho salmon along the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 205-232.

Trudel, M., Baillie, S., Parken, C., and O'Brien, D. 2008. Average growth for coho salmon in southern British Columbia. pp. 82-83 In Irvine, J. and B. Crawford (Eds). 2008. *State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems.* Canadian Science Advisory Research Document 2008/013: http://www.dfo-mpo.gc.ca/csas/Csas/Publications/ResDocs-DocRech/2008/2008_013_e.htm

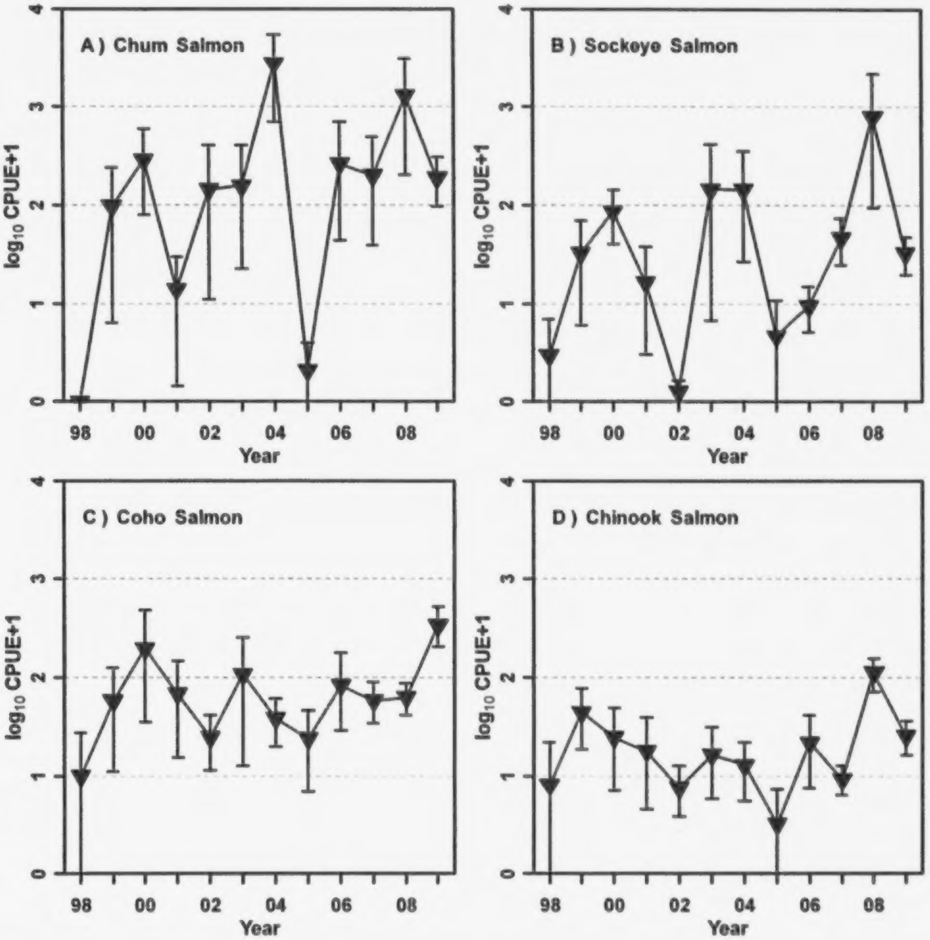


Figure 1. Catch-per-unit-effort (CPUE) of juvenile Chum salmon, Sockeye salmon, Coho salmon, and Chinook salmon on the continental shelf off the west coast of Vancouver Island in June-July 1998-2009. Average CPUE and 95% confidence intervals were obtained by bootstraping.

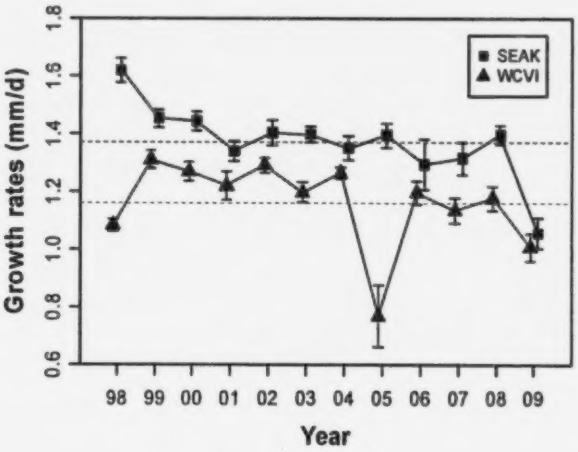


Figure 2. Growth rates (May-October) of juvenile Coho salmon off the west coast of Vancouver Island (red triangles) and Southeast Alaska (blue squares). The blue and red dotted lines represent the 1998-2009 average values for Southeast Alaska and the west coast of Vancouver Island, respectively. The error bars are 2 times the standard error. Details on the procedure used to estimate growth rate are provided in Trudel et al. (2007).

PACIFIC HAKE (*MERLUCCIUS PRODUCTUS*) DISTRIBUTION AND ABUNDANCE ALONG WEST COAST OF CANADA AND THE UNITED STATES, 1998-2009

Chris Grandin, Ken Cooke, and John Holmes, Fisheries and Oceans Canada

Between June 29 and September 8, 2009, Canada and the United States conducted a joint acoustic-trawl survey to assess the distribution and abundance of the offshore Pacific hake (*Merluccius productus*) stock. Here we present the results of the 2009 survey and discuss these results and implications on the stock.

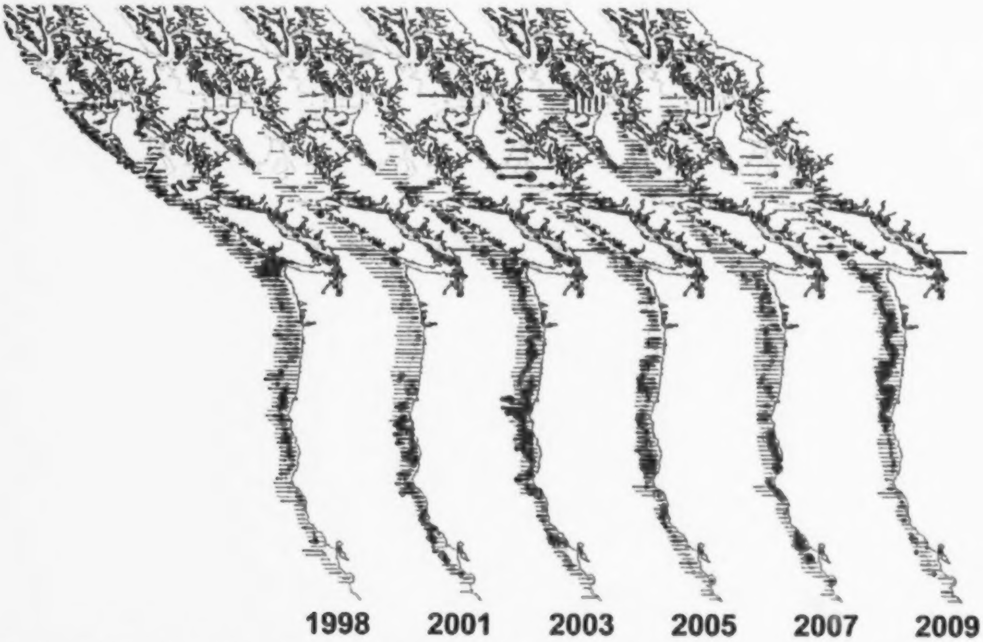


Figure 1: Offshore Hake abundance time series estimated by the Canada-US Pacific Hake Acoustic Trawl Survey (1998-2009). Black lines show survey grid, cyan line is the 200m depth contour (continental shelf-edge) and the red circles indicate hake acoustic backscatter along transects with size proportional to the maximum among years. Figure provided by Rebecca Thomas, Nat. Marine Fish. Serv., Northwest Fish. Center, Seattle, WA.

The offshore Pacific Hake stock is the largest of three stocks along the west coast of North America. It is also the most abundant groundfish in the California current system and is an important commercial species in both Canada and the United States. Hake disperse from winter spawning grounds off southern California to northern feeding areas off the coasts of northern California, Oregon, Washington and British Columbia during the summer months (Figure 1) where they traditionally form dense midwater W-shaped aggregations at depths of 150-300 m along the edge of the continental (200 m depth contour) during daylight hours (Dorn 1995). This pattern has changed this year, however, with the W-shaped aggregations mostly being replaced with far less dense clouds of Hake which aggregate much closer to the bottom, and in addition extremely large numbers of Humboldt Squid (*Dosidicus Gigas*) were found both above and in mixture with the Hake schools.

Acoustic trawl surveys to assess the distribution and abundance of hake have been conducted since 1977 by the United States and jointly with Canada since 1992, under the auspices of the International Hake Treaty, which recognizes that this stock is a transboundary resource. These surveys have covered the full distribution of hake since 1992 using standardized protocols and sonar equipment. The 2009 survey was conducted by the NOAA Ship *Miller Freeman* in U.S. waters and the CCGS *W.E. Ricker* in Canadian waters. The 2009 survey covered more than 12,000 nautical miles on 133 transects, with 112 midwater trawls to confirm species composition and to obtain measurements of length, weight, sex and age samples during 71 days of ship time.

Hake were distributed from Monterey Bay (36.8°N) northwards to Dixon Entrance (54.6°N) in 2009, with less than typical shelf-edge aggregations of hake observed off the Washington, Oregon, and northern California coasts. Further north in Canadian waters, hake distribution was sparse, with most hake located in Queen Charlotte Sound, Juan de Fuca Strait, and Dixon Entrance. Total estimated biomass, as accepted by the Stock Assessment and Review (STAR) panel for 2010 (median) is 1.735 million metric tonnes with a 5% and 95% credible interval of 0.695 and 4.119 million metric tonnes (Martell, 2010). Figure 2 presents the time series of Pacific Hake biomass since 1966, including the estimate for 2010. The biomass in 2010 represents a depletion level of 37% of unfished biomass that is assumed to have been in existence in 1966 (Figure 3).

The 2009 survey biomass estimate is highly uncertain due to the presence of Humboldt squid in target verification tows. Acoustic signatures that were virtually indistinguishable often resulted in a tow of either 100% hake, 100% Humboldt squid, or a mixture of the two. Due to this uncertainty in the estimate the recent STAR panel review discarded the 2009 estimate for the purposes of stock assessment, so unlike previous reports we will not report the acoustic index time series but rather the accepted model biomass trajectory for the stock. Figure 4 shows the recruitments by year based on commercial catch at length and age data. The current stock assessment does not estimate 2005 or 2006 as particularly strong year classes (Figure 4); in fact they are below the long term mean while the acoustic survey estimates these to be extremely abundant.

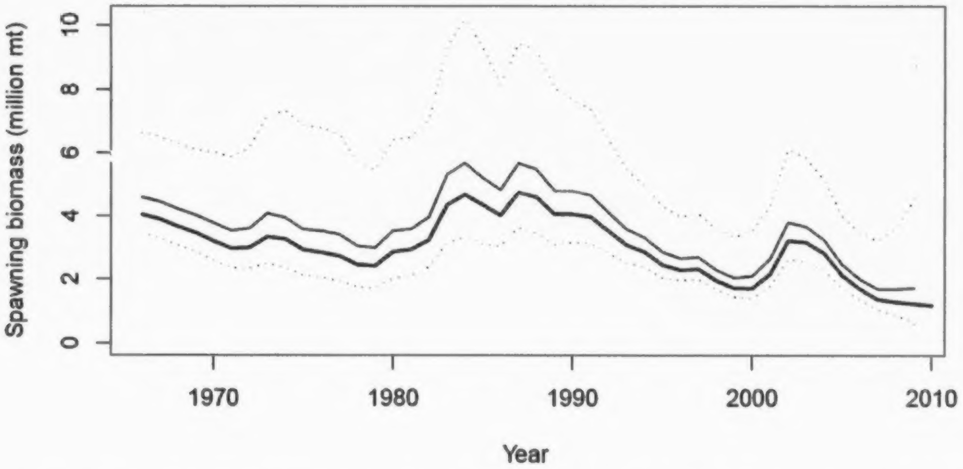


Figure 2: Spawning stock biomass maximum likelihood estimates (thick line) and median estimates (thin line). Dotted lines are 0.025 and 0.975 quantiles. (figure from Martell, 2010).

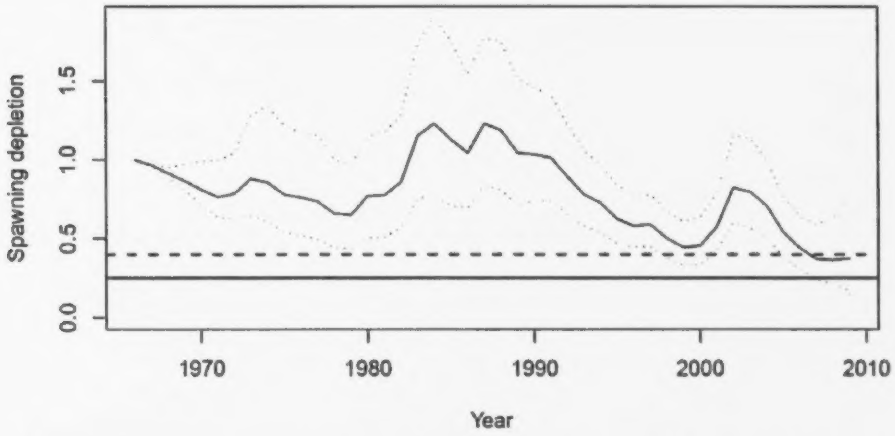


Figure 3: Spawning stock depletion with 40% (dotted) and 25% (solid) unfished biomass levels. Dotted lines are 0.025 and 0.975 quantiles. (figure from Martell, 2010).

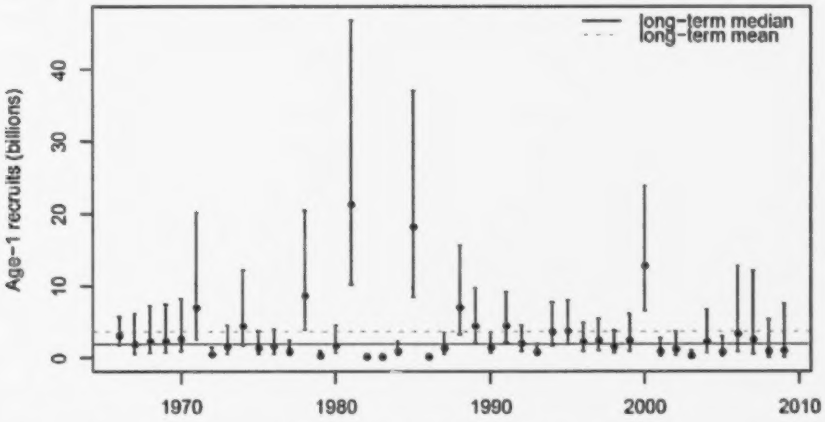


Figure 4: Age-1 recruitment and associated 0.025 and 0.975 quantiles. Long term average and median recruitments are shown by horizontal lines (figure from Martell, 2010).

In Canada, a spatial shift for the species from South to North has continued in 2009, and the fishery in Canada has shown a clear impact of this shift. Figure 5 outlines this shift,, showing a clear change in the fishery from traditional southern fishing spots to the North in the past three years. Also there has recently (2007-2009) been a large increase in the targeting of Pacific Hake in the Strait of Juan de Fuca to compensate for the lack of fish offshore of Vancouver Island.

The distribution of Hake shifts northward and southward between biannual Hydroacoustic Hake surveys in response to climate-related changes in ocean conditions, particularly sea surface temperature (SST) during the northward migration (Mar-July) and coastal upwelling. In 1998, hake were found in Alaskan waters to 58°N as a result of the strong 1997-98 El Niño event (Wilson et al. 2000), which warmed coastal waters and enhanced poleward current flow during the winter and early spring. In contrast, few hake were found north of 48°N in 2001 owing to the 1999-2001 La Niña event (Guttormsen et al. 2003), which cooled coastal surface waters and reduced poleward transport in spring.

That these differences in distribution represent a shift in stock location rather than summer range extensions is illustrated by the fact that 49% of hake biomass was observed in Canadian waters in 1998 (Wilson et al. 2000), but only 10% (in three isolated spots – Fig. 1) in 2001 (Guttormsen et al. 2003). Historically, the area from the mouth of Juan de Fuca Strait (48.25° N) to La Pérouse Bank (48.8° N) were the most productive fishing grounds for the Canadian hake fishery. However, there has been a substantial decline in hake biomass in this area since the 2003 survey (Fig. 1), which is most clearly illustrated by the 2007 and 2009 data, and as a result the fishery has shifted to Queen Charlotte Sound. Hypotheses to explain this decline in hake abundance on traditional Canadian fishing grounds continue to be unclear, but are not related to differences in survey methodology or timing as all surveys since 1995 have followed standardized protocols and were conducted between June and September when hake have completed their annual northward migration and are fully available to the survey (Nelson and Dark 1985).

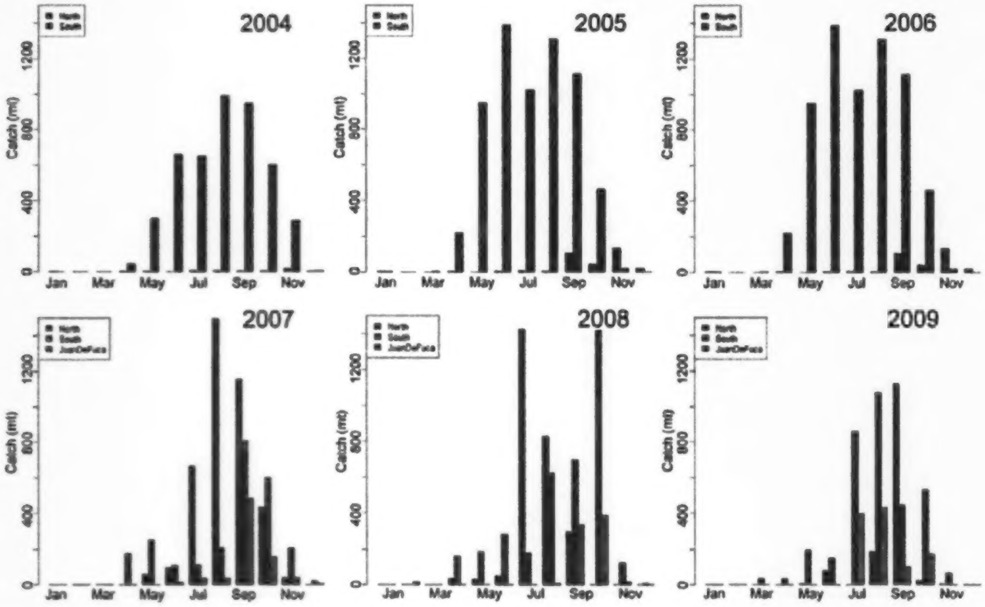


Figure 5: Landings of Pacific Hake in Canadian waters by month and area. North includes statistical areas 5A, 5B, 5C, 5D, and 5E. South includes areas 3B, 3C, and 3D. Juan De Fuca includes area 4B, minor area 20 only.

The 2007 and 2009 surveys were notable for the capture of Humboldt squid (*Dosidicus gigas*) during biological sampling at depths exceeding 250 m offshore of the continental shelf along Vancouver Island and the Queen Charlotte Islands. Humboldts underwent a rapid range expansion into the northern California Current between 2002 and 2006 (Field et al. 2007), but the 2007 survey was the first that captured Humboldt squid exclusively in Canadian waters and these captures were associated with unusual hake acoustic signs. Based on the hake acoustic signs, hake exhibited diffuse, less dense aggregation patterns when Humboldt squid were captured and we hypothesize that Humboldt predation on hake led to increased swimming activity and dispersal of hake, resulting in these atypical patterns observed near the shelf-break (Holmes et al. 2008). The implications of this hypothesis for hake acoustic surveys are significant since the acoustic signs associated with mixed hake-squid catches likely would be attributed to small meso-pelagic fishes (e.g., myctophids or lanternfishes) in the absence of evidence to the contrary, i.e., hake in these mixtures may not contribute to overall biomass estimates (Holmes et al. 2008). In 2009, the abundance of Humboldts increased to the point that the ability for acoustics to distinguish the difference between Hake and Humboldt squid became nearly impossible and the survey biomass point was removed from the assessment model.

References

Dorn, M.W. 1995. *The effects of age composition and oceanographic conditions on the annual migration of Pacific whiting,* Merluccius productus. Calif. Coop. Oceanic Fish. Invest. Rep. 36: 97-105.

Field, J.C., K. Baltz, A.J. Phillips, and W.A. Walker. 2007. *Range expansion and trophic interactions of the jumbo squid,* Dosidicus gigas*, in the California Current*. Calif. Coop. Oceanic Fish. Invest. Rep. 48: 131-145.

Guttormsen, M.A, C.D. Wilson, K. Cooke, M.W. Saunders, D.R. McKelvey, and R. Keiser. 2003. *Echo integration-trawl survey of Pacific hake,* Merluccius productus, *off the Pacific coast of the United States and Canada during June-August 2001*. U.S. Dept. Comm., NOAA, AFSC Processed Rep. 2003-12, 80 p.

Holmes, J., K. Cooke, and G. Cronkite. 2008. *Interactions between jumbo squid (Dosidicus gigas) and Pacific hake (Merluccius productus) in the northern California Current in 2007*. Cal. Coop. Oceanic Fish. Invest. Rep. 49 (accepted for publication pending minor revisions).

Martell, S., 2010, *Assessment and Management Advice for Pacific Hake in U.S. and Canadian Waters in 2010*. in publication.

Nelson, M. O., and T. A. Dark. 1985. Results of the coastal Pacific hake, *Merluccius productus*, survey. *Mar. Fish. Rev*. 47: 82–94.

Wilson, C.D., M.A. Guttormsen, K. Cooke, M.W. Saunders, and R. Kieser. 2000. *Echo integration-trawl survey of Pacific hake,* Merluccius productus, *off the Pacific coast of the United States and Canada during July-August, 1998,* 103 p. U.S. Dept. Comm., NOAA Tech. Memo, NMFS-AFSC-118.

Wilson, C. D., and M. A. Guttormsen. 1997. *Echo integration-trawl survey of Pacific whiting,* Merluccius productus, *off the west coasts of the United States and Canada during July-September 1995*, 70 p. U.S. Dept. Comm., NOAA Tech. Memo, NMFS-AFSC-74. 89

OCEAN DISTRIBUTION OF TWO DEPRESSED SOCKEYE SALMON STOCKS

Marc Trudel, Strahan Tucker, and John Candy, Fisheries and Oceans Canada

Little is known of the ocean distribution and migration of endangered or threatened stocks of Sockeye salmon in the Fraser River (e.g. Cultus Lake) and Columbia River (e.g. Redfish Lake), thus making it difficult to assess how ocean conditions affect the recruitment of these stocks, and hence, to forecast their returns. The mass marking of endangered and threatened stocks of Sockeye salmon, in recent years with coded-wire tags (CWT) along with DNA analyses now makes it possible to track their ocean migration.

Five juvenile Cultus Lake Sockeye tagged by DFO with CWT, were recovered off the coast of British Columbia in late June 2008 and 2009 (Table 1; Figure 1). DNA analyses performed on over 1,800 juvenile Sockeye salmon collected off the coast of British Columbia in 2007-2009 revealed an additional six juvenile Cultus Lake Sockeye salmon in late June 2008 and two in late June- early July 2009 (Figure 1). The ocean migration speed, assuming that these fish were swimming in a straight line and initiated their downstream migration on May 1, ranged from 14 km/d-19 km/d, or 1.1-1.4 body lengths per second (BL/s) (Table 1). Ocean migration speed of Cultus Lake Sockeye salmon smolts obtained by acoustic telemetry ranged from 10-30 km/d and are somewhat larger than those we derived here, possibly because they used larger fish (Welch et al. 2009). Correcting for body size differences provided similar results (1.1-1.4 BL/s vs 0.5-2 BL/s).

We also recovered seven juvenile Redfish Lake Sockeye salmon tagged with a CWT in June-July 2007-2009, including three in 2009 (Table 1; Figure 1). In addition, DNA analyses revealed one additional juvenile Redfish Lake Sockeye salmon in late June 2007 and five more in late June 2008 (Figure 1). These fish traveled approximately 1,450 km in the Snake River and Columbia River and another 350-1,150 km in the ocean in less than 70 days. Assuming it takes 20 days to complete the downstream migration, these fish were estimated to swim at 14-35 km/d, or 1.2-2.6 BL/s. This is similar to their theoretical optimal cruising speed at 15°C (Trudel and Welch 2005), indicating that that they undertake a rapid northward migration that quickly brings them well beyond the Columbia River estuary and plume to expose them to ocean conditions prevailing on the west coast of British Columbia, and subsequently to those in Alaska.

References:

Trudel, M., and D.W. Welch. 2005. Modeling the oxygen consumption rates of Pacific salmon and steelhead trout: model development. *Trans. Am. Fish. Soc.* 134: 1542-1561.

Welch, D.W., Melnychuk, M.C., Rechisky, E.R., Porter, A.D., Jacobs, M.C., Ladouceur, A., McKinley, R.S., and Jackson, G.D. 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. *Can. J. Fish. Aquat. Sci.* 66: 736-750.

Origin	Tag code	Recovery Date	FL (mm)	Latitude	Longitude	Distance (km)	Speed (km/d)
RL	10-82-77	06/29/2007	170	52°27' N	130°14' W	2,401	31.2*
RL	10-82-77	07/01/2007	162	54°15' N	131°41' W	2,598	29.0*
RL	10-17-81	06/21/2008	138	49°03' N	126°07' W	1,800	13.6*
RL	09-46-29	06/28/2008	193	54°28' N	131°36' W	2,530	32.8*
RL	10-95-82	06/18/2009	123	48°29' N	125°51' W	1,769	14.8*
RL	09-01-47	06/23/2009	179	50°56' N	129°00' W	2,178	27.2*
RL	09-01-47	06/24/2009	195	52°29' N	130°30' W	2,414	34.7*
CL	18	06/28/2008	176	54°33' N	132°22' W	1,138	19.9†
CL	18	06/28/2008	176	54°26' N	131°24' W	1,088	18.0†
CL	08	06/24/2009	165	52°29' N	130°30' W	844	15.3†
CL	08	06/24/2009	167	52°32' N	130°45' W	864	15.7†
CL	18-57-56	06/24/2009	168	52°32' N	130°45' W	864	15.7†

Table 1. Recovery location of juvenile coded-wire tagged Cultus Lake (CL) and Redfish Lake (RL) Sockeye salmon and estimated migration distance from the release site and ocean migration speed.

** Migration speed estimated assuming that Redfish Lake Sockeye smolts enter the ocean on May 27.*

† Fence counts were used to assess the 50% smolt migration date out of Cultus Lake (M. Bradford, personal communication). We then assumed that the smolts took 6 days to complete the downstream migration (Welch et al. 2009).

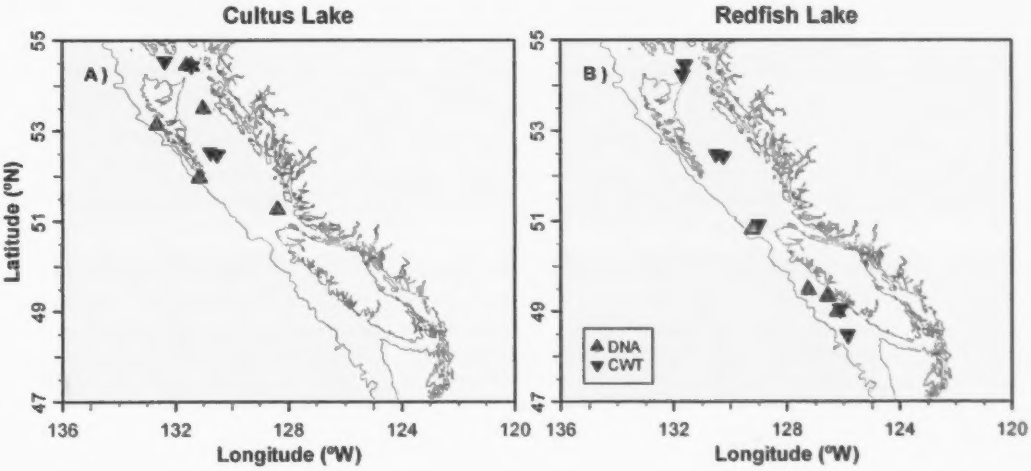


Figure 1. Recovery locations of juvenile A) Cultus Lake and B) Redfish Lake Sockeye salmon caught in British Columbia in June-July 2007-2009 identified by CWT or DNA analysis. Juvenile Sockeye salmon were caught using a rope trawl towed at the surface for 30 minutes at 5 knots. Sampling effort was limited to the continental shelf, as previous surveys indicated that juvenile Sockeye salmon were restricted to the continental shelf at this time of year. The symbols indicate locations where at least one individual was recovered. Thus, they may contain multiple recoveries.

SMALL-MESH BOTTOM-TRAWL SURVEYS: FURTHER INCREASES IN SMOOTH PINK SHRIMP BIOMASS IN 2009

Ian Perry, Jim Boutillier and Dennis Rutherford, Fisheries and Oceans Canada

Bottom trawl surveys using a small-mesh net (targeting the smooth pink shrimp *Pandalus jordani*) have been conducted during May since 1973 in two regions off the west coast of Vancouver Island (Figure 1).

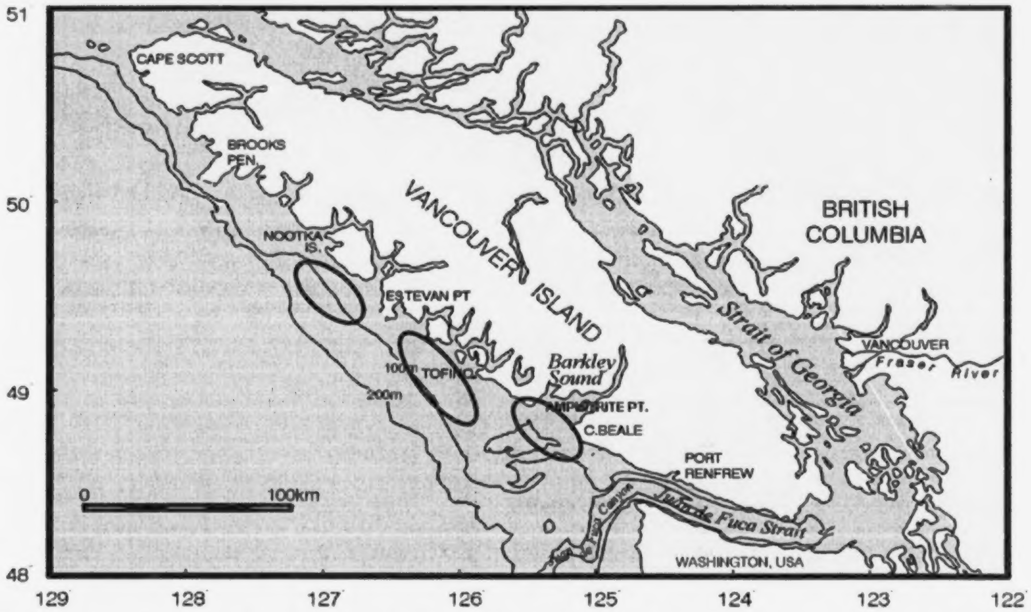


Figure 1. Map showing the three main shrimp (Pandalus jordani) fishing grounds off Vancouver Island (red ovals). The Nootka (Area 125) and Tofino (Area 124) Grounds, which have had fishery-independent surveys since 1973, are the northern and middle ovals, respectively.

Recent surveys found the biomass of *Pandalus jordani* shrimp off central Vancouver Island had increased in 2008 and again in 2009, from very low levels during 2004-2007. Such increases appear related to colder water temperatures in 2007 when the shrimp were young (this species has a 2-yr time lag from hatch to recruitment at age-2) and to low abundances of Pacific hake (a potential shrimp predator) in May surveys in 2008 and 2009. Biomass trends of key flatfish indicator species were equivocal in 2009, with some species up slightly (such as Arrowtooth flounder) and others down slightly (such as Pacific halibut). Time series of pelagic, demersal and benthic taxa suggest surveyed biomasses tended to be low from the mid-1970s to mid-1980s and high in the early 2000s.

Recent trends (since 2005; Figure 3) in the distribution of biomass among taxa are not significantly different from that expected by chance, i.e. 25% of taxa have low biomass, 50% of taxa have about average biomass, and 25% of taxa have high biomass. This contrasts with a year such as 2002, in which 6% of taxa had low biomass and 62% had high biomass, which is significantly different from expectation. Note that some of the biomass fluctuations of fish species may be due to movement into and out of the survey area (the survey area is based on suitable shrimp habitat); this is currently under investigation.

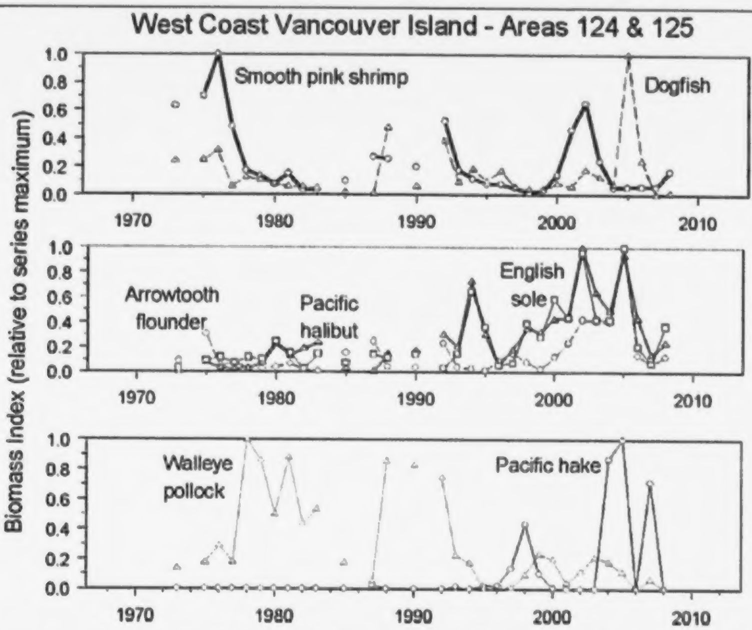


Figure 2. Time series of normalised (to maximum biomass) survey catches of smooth pink shrimp, dogfish, Pacific halibut, Arrowtooth flounder, English sole, Pacific hake and walleye pollock. Sampling was in May of each year.

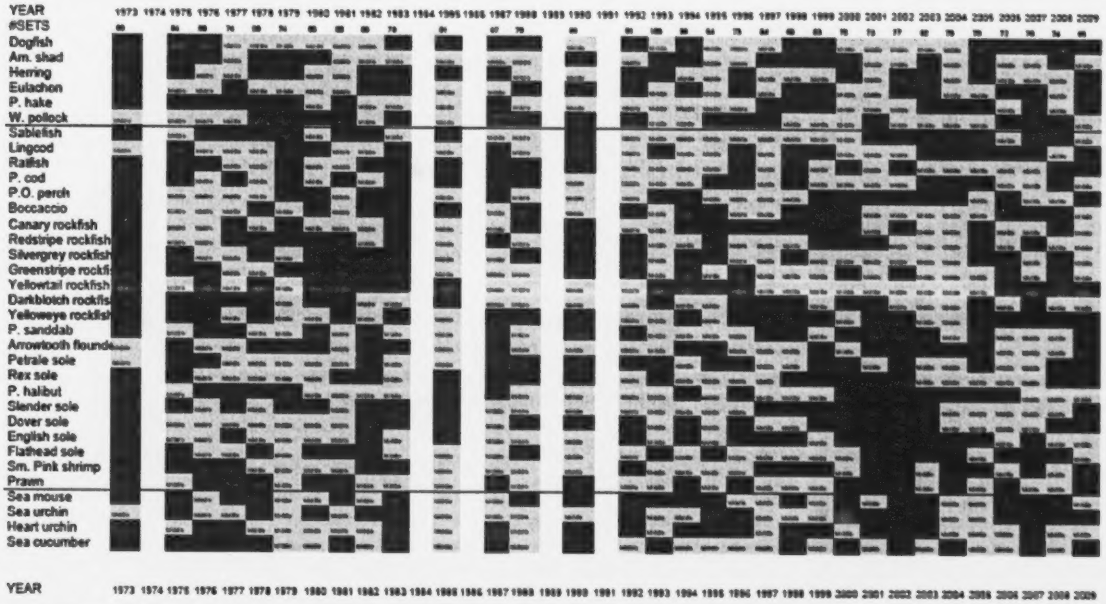


Figure 3. Biomass time series of relative biomass in May of "key" species sampled during small-mesh bottom trawl surveys off the west coast of Vancouver Island, 1973-2008. Each year is coded based on its entire time series, i.e. ≤ 25th percentile (blue), 25th to 75th percentile (yellow), and ≥ 75th percentile (red). Rows are grouped by Pelagic, Demersal (fish), Benthic (invert) taxa.

COHO SALMON SURVIVALS IN SOUTHERN BRITISH COLUMBIA

James R. Irvine[1] and David Blackbourn[2]
[1]Pacific Biological Station Nanaimo [2]Private consultant, Nanaimo

Here we build on work presented in last year's report, focusing on Coho salmon populations in the Strait of Georgia (SoG) and the West Coast of Vancouver Island (WCVI). Last year's categorical forecast of relatively good marine survivals for Coho returning in 2009 (Irvine and Blackbourn 2009) was borne out. (Marine survival is the proportion of smolts leaving their natal river that survive the next 18 months and are either caught or escape fisheries to spawn). Coho that returned to the SoG and WCVI in 2009 survived approximately twice as well as Coho the previous year (Fig. 1).

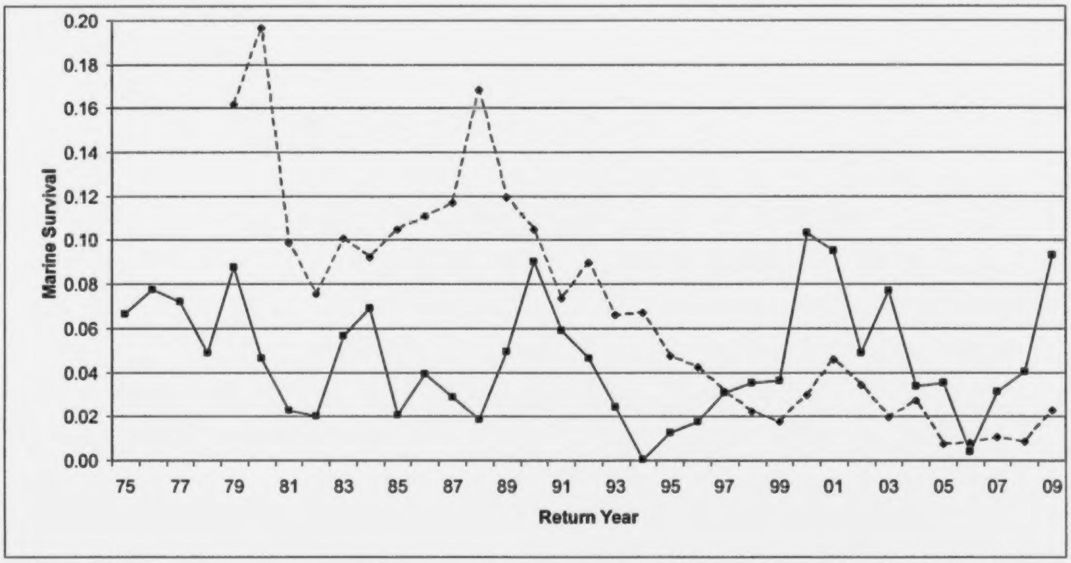


Figure 1. Time series of average marine (smolt to adult) survivals for Coho salmon returning to the SoG (dashed line) and WCVI (solid line). Values plotted are the average of separate annual estimates for hatchery and wild Coho salmon (no wild survival estimates for SoG during 1981-1986 and WCVI pre-1999).

Linear multiple regressions were performed for each area for the complete time series of marine survival estimates and for the most recent 10 years (Fig. 1). Using explanatory environmental variables from the sea water entry year that were significantly correlated with these survivals, we developed several models for each area and time series. The best model was the one with the lowest AICc and generally highest adjusted r^2 value, which we used to forecast survivals for Coho salmon that will return in 2010 (Table 1). Average to above-average survivals are expected for both the WCVI and the SoG.

It is important to realize that good survivals do not necessarily mean good returns. Coho salmon that will return in 2010 are the progeny of smolts that went to sea in the spring of 2006, many of which experienced low marine survivals, producing low spawning escapements in 2007. Even with relatively high survivals, because of the low spawner numbers in 2007, returns in 2010 are expected to be modest.

Area	**Base Period**	**Best Model Parameters**	R^2 **adj**	**Mean Survival (%)**	**Forecast Survival (%)**	**Forecast Survival Colour**
WCVI	Complete time series	PDO (April-June), N. "chaetognaths" SWCVI offshore	0.55	4.7	6.9	Green
WCVI	Last 10 years	PDO (April-June), S. "chaetognaths SWCVI shelf, N. "chaetognaths" SWCVI offshore	0.97	5.6	10.1	Green
SoG	Complete time series	Entrance Isle July SST, Langara April salinity, *T. spinifera* SWCVI shelf	0.75	6.8	4.4	Yellow
SoG	Last 10 years	Langara July salinity, *T. spinifera* SWCVI shelf	0.68	2.1	4.1	Green

Table 1. Best model parameters and predicted marine survivals for Coho salmon returning in 2010, based on correlations during two base periods (green = > 0.5 Standard Deviations (SD) above mean survival; yellow = mean survival ± 0.5 SD; red = < 0.5 SD below mean survival).

We thank Steve Baillie for providing updated Coho marine survival data, and Dave Mackas for providing zooplankton data.

Reference

Irvine, J. and D. Blackbourn. 2009. Coho – southern BC populations doing poorly but some survival improvements expected, pp 101-102 *in* Crawford, W.R. and Irvine, J.R. 2009. *State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems.* DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022, vi + 121 p.

TRENDS OF CHINOOK SALMON ABUNDANCE IN FISHERIES MANAGED UNDER THE PACIFIC SALMON TREATY

Gayle Brown, Dawn Lewis, Charles Parken, and Antonio Velez-Espino
Fisheries and Oceans Canada

Under the jurisdiction of the Pacific Salmon Treaty (PST), 30 Chinook salmon stock aggregates and 25 fisheries distributed between southeast Alaska and northern Oregon are managed annually to either projected landed catch targets or are limited by maximum allowed exploitation rates. Estimates of escapements or terminal runs of mature fish for each of the stock aggregates and estimates of numbers of Chinook landed or released in the PST fisheries are assembled annually and provide some of the crucial data inputs to the calibration of the Coast-wide Chinook Model (CM). The Chinook stocks (consisting of both wild- and hatchery-origin fish) and fisheries represent nearly all Chinook and fishing-related impacts known to occur within the PST jurisdiction.

A result of the CM calibration procedure is a time series of aggregate Chinook abundance estimates for each fishery starting with 1979 and ending with the most recently completed fishing year. An abundance forecast is also generated for the upcoming fishing year and is the basis for establishing the annual catch targets in three highly mixed-stock ocean fishery areas (southeast Alaska, Northern BC including areas around the Queen Charlotte Islands, and west coast Vancouver Island).

Time series of abundance indices (AIs) are annually derived and reported to the Pacific Salmon Commission in technical reports prepared by the bilateral Chinook Technical Committee (e.g., TCCHINOOK 09(1), 2009 Annual Report of Catches and Escapements, TCCHINOOK 09(3), 2009 Annual Report of Exploitation Rate Analysis and Model Calibration available at http://www.psc.org/publications_tech_techcommitteereport.htm#TCCHINOOK).

The AIs are derived by dividing the annual estimated Chinook abundance in any one fishery by the average from the 1979-1982 'base period'. These provide a means to assess temporal and spatial trends in the relative abundance of Chinook stocks contributing to regional fisheries.

The time series of AIs for some of the major northern ocean fisheries (Figure 1) show generally that abundance has been consistently higher than in southern fisheries (Figure 2). More interestingly, Chinook abundance has reached a high of more than twice the base period average (BPA) in the most northerly fishery (southeast AK troll) and a low of less than half the BPA in the most southerly fishery (combined WA and OR ocean troll).

There have been two obvious peaks in abundance (1988 and 2003) in the two most northerly fisheries, SEAK troll and Northern BC troll, with lows just dipping below the BPA (Figure 1). In southerly fisheries (e.g., WCVI troll and WA/OR troll), there have been corresponding smaller peaks, with abundances mostly below the BPA, and a third peak is developing (Figure 2). Abundances in the 'inside' area fishery, combined Georgia Strait and Juan de Fuca sport in BC, declined below its BPA early in the time series, with abundances of about half the BPA during the last two decades. 2009 AI's were modestly greater than in 2008 in all cases, with the exception of WA/OR that was somewhat reduced.

The 2010 CM calibration projects a modest increase for most Chinook fisheries and a large increase for the WCVI and WA/OR troll fisheries. The large increases are due to expectations for large abundances of Lower Fraser River and most Columbia River stocks that entered the sea in 2008 and produced record high, or nearly so, returns of jack Chinook (precocious males) to spawning grounds in 2009.

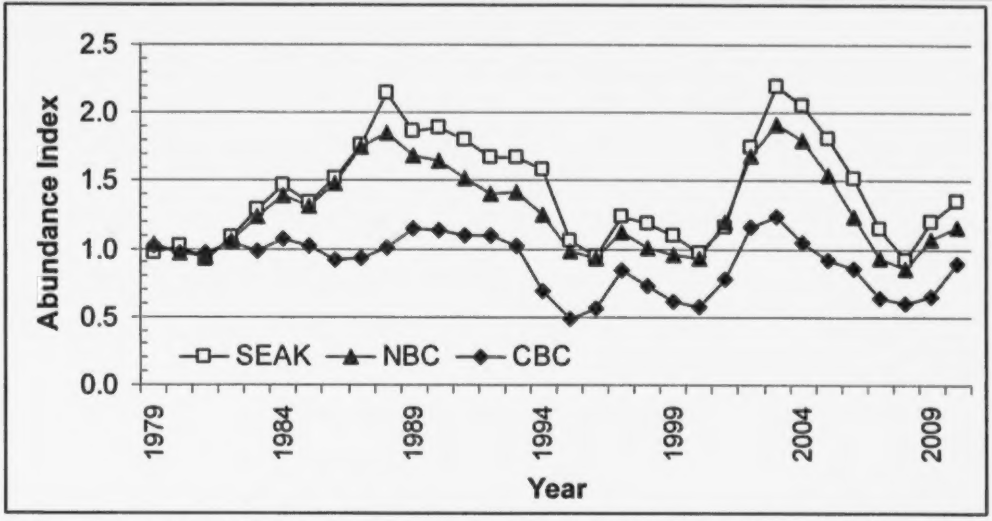


Figure 1. Time series of Chinook salmon abundance indices for three major northerly PST fisheries, 1979-2010. The fisheries are southeast Alaska troll (SEAK), northern BC troll in statistical areas 1-5 (NBC) and central BC troll in statistical areas 6-12 (CBC). Please note that 2010 values are forecasts resulting from the March 2010 calibration of the Coast-wide Chinook Model.

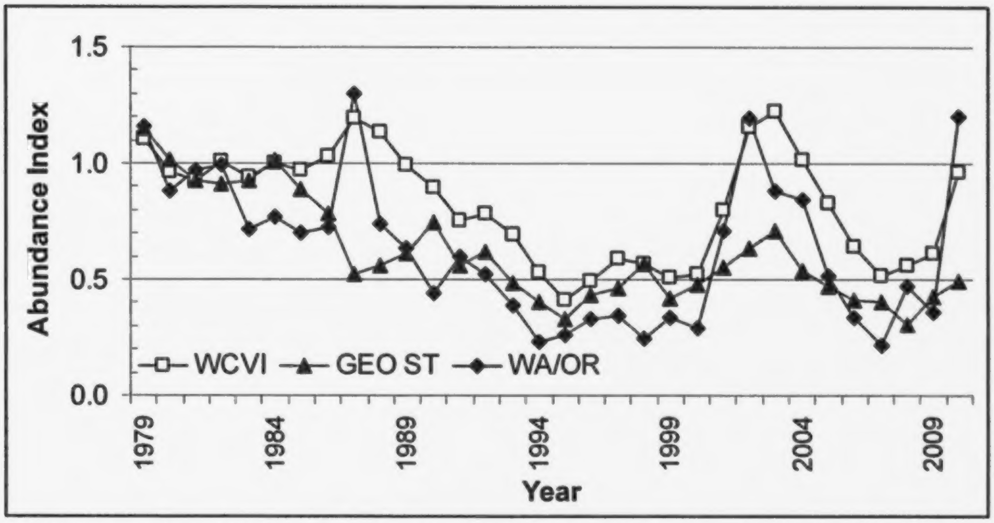


Figure 2. Time series of Chinook salmon abundance indices for three southerly PST fisheries, 1979-2010. The fisheries are west coast Vancouver Island troll (WCVI), Georgia Strait and Juan de Fuca Sport (GEO ST), and Washington and northern Oregon ocean troll (WA/OR). As in Figure 1, the 2010 values are forecasts.

ALBACORE TUNA ABUNDANCE IN BC WATERS: ABOUT AVERAGE IN 2009

John Holmes, Fisheries and Oceans Canada

Tunas, marlins, and swordfishes are collectively known as highly migratory species (HMS) because they spend most of their lives in open ocean waters where they travel large distances every year. Albacore tuna (*Thunnus alalunga*) is widely distributed in the North and South Pacific Ocean and is the most economically important HMS to Canadians in British Columbia. There are two distinct stocks of albacore in the Pacific Ocean, one in the South Pacific and one in the North Pacific. These two stocks do not mix with each other. Canadian trollers have been fishing the North Pacific albacore stock since the mid-1930's (Figure 1). This fishery uses jigs in surface waters to target juvenile fish ranging from three to five years of age, and lasts from late June through the end of October.

Canadians fish for North Pacific albacore in domestic waters of the BC coast, in the Exclusive Economic Zone (EEZ) of the United States, and in the high seas outside the US and Canadian EEZs. Annual catch has averaged 5,793 t since 2000, ranging between a low of 4,816 t in 2000 and a peak catch of 7,905 t in 2004; the 2009 catch was 5,885 t. More than 80% of the annual Canadian catch and effort since 2000 has occurred in the coastal waters of Oregon and Washington through access provisions in the Canada-U.S. Pacific Albacore Tuna Treaty. Albacore catch in the coastal waters of BC was 398 t in 2009 and has ranged between 202 t (2008) to 1,616 t (2005) since 2000.

The juvenile albacore targeted by the Canadian fleet undergo extensive annual migrations across the North Pacific Ocean. They appear in subtropical coastal waters off southern California and Mexico in May and June and move north to temperate waters off Oregon, Washington, and BC as these waters warm. The distribution and abundance of albacore in coastal waters is related to sea surface temperatures (SST) greater than 14°C (Alverson 1961; Clemens 1961; Hart 1973), shoreward intrusions of warm oceanic waters into cooler coastal waters (Laurs et al. 1984), and the location of key temperature fronts (Zainuddin et al. 2008). Although albacore are caught at temperatures ranging from 14 to 19 °C, about 80% of the fish caught annually by the Canadian fleet are in waters between 16 and 17°C (Fig. 1).

Stock assessment scientists use catch rates based on catch-per-unit-effort (CPUE), which is calculated as total catch (in kg or number of fish) divided by the effort to achieve that catch (in vessel-days) as an indicator of fish abundance. The albacore CPUE in BC coastal waters averaged 560 kg/vessel-day for the 2000-2008 period and was 562 kg/vessel-day in 2009. A standardized index of albacore abundance relative to average conditions is produced by subtracting the multi-year mean from the annual catch-rates and dividing by the standard deviation (a measure of variability in the data). Positive values indicate abundance is above average, and negative values are below average. Similarly, June sea surface temperature (SST) anomalies (monthly average temperature minus the multi-year monthly average) at Amphitrite Point is used as a predictor of the spatial and temporal availability of "tuna waters" (SST > 14 °C) within the Canadian EEZ. A plot of the albacore abundance index with June SST anomalies shows that albacore abundance generally increases when June SST is above average and decreases when SST is below average (Fig. 2). Statistically, June SST anomalies are strongly correlated with the albacore abundance index and account for 44% of the variation in annual albacore abundance in coastal BC waters. Although SST in June 2009 was slightly above average, albacore abundance was average relative to the 2000-2008 period. The distribution of albacore in BC waters also changes as abundance changes. For example, during 2006 when abundance was high (Fig. 2), albacore were as far north as Haida Gwaii, whereas in 2000-01 abundance and SST were well below average, reflecting cool ocean conditions coinciding with a strong La Niña event, and albacore in BC waters were concentrated further south off the west coast of Vancouver Island.

Ocean conditions along the west coast of North America appear to have switched to warming in December 2009 as part of an El Niño event. If these conditions continue to prevail in 2010, then increased albacore abundance and a broader distribution within the coastal waters of BC can be expected through the albacore fishing season (June-Oct).

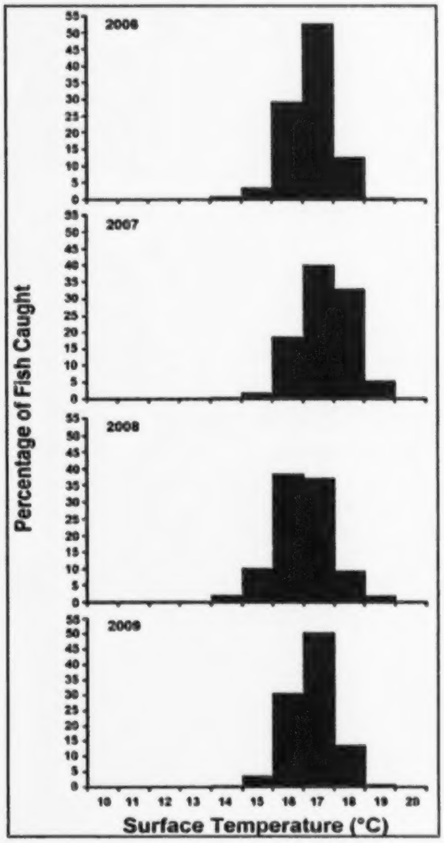
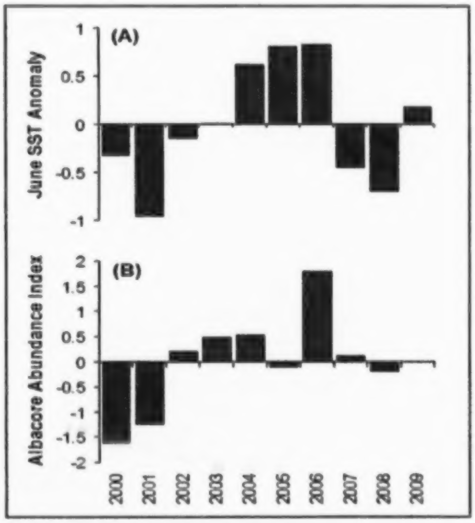


Figure 1 (left). Surface water temperatures at which the Canadian fleet caught North Pacific albacore in 2006 (N = 731,657 fish), 2007 (N = 692,464 fish), 2008 (N = 901,323 fish), and 2009 (N = 910,457 fish).

Figure 2 (below). June sea surface temperature (SST) anomalies at Amphitrite Point Lighthouse on the southwest coast of Vancouver Island (A) and annual abundance index values (standardized albacore catch rate anomalies) in BC waters (B). Zero in both figures represents average conditions for the 1971-2000 (SST) and 2000-2008 (catch rates) periods.



References

Alverson, D.L. 1961. Ocean temperatures and their relation to albacore tuna (*Thunnus germo*) distribution in waters off the coast of Oregon, Washington, and British Columbia. *J. Fish. Res. Board Can. 18*: 1145-1152.

Clemens, H.B. 1961. The migration, age, and growth of Pacific albacore (*Thunnus germo*), 1951-1958. *Calif. Dept. Fish Game Fish. Bull. 115*: 128 p.

Hart, J.L. 1973. Pacific fishes of Canada. *Bull. Fish. Res. Board Can.* 180.

Laurs, R.M., Fielder, P.C., Montgomery, D.R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep-Sea Res. 31*:1085-1099.

Zainuddin, M., Saitoh, K., and Saitoh, S.-I. 2008. Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western North Pacific Ocean using remotely sensed satellite data. *Fish. Oceanogr. 17*: 61–73.

GEORGIA BASIN

FRESHWATER FLUX ON THE BRITISH COLUMBIA COAST

John Morrison, Vynx Design Inc.

Background

The drainage basins supplying water to the British Columbia coast cover an area of approximately 610,000 km^2. Rivers along the coast originate in variety of climatic zones resulting in various flow patterns. Rivers in coastal plains have minimal flow in the summer and peak flows in late fall or early winter. Rivers originating in the coastal mountains follow the same pattern in the warm months but store precipitation as snow cover over the winter months. Coastal mountain rivers have peaks in both the early fall and early spring. However the majority of the area in the drainage basins is located inland. This means that the fresh water flows are dominated by climate zones that are remote from the coast. Here the flow is dominated by winter storage, with minimal impact from autumn precipitation. Peak flow occurs in late May or early June. River flow into the ocean is called "discharge " or "runoff"

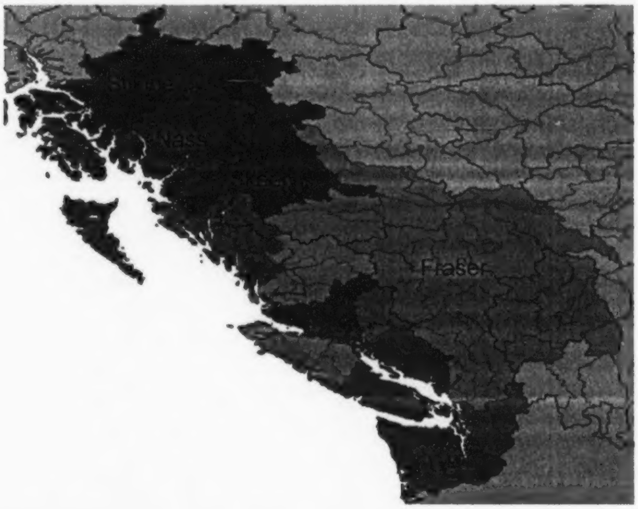


Figure 1: Pacific drainage basins of British Columbia.

Runoff estimation

River discharge is estimated at gauging stations by measuring the river height and calculating the flow based on corresponding cross sectional areas and water velocities. Unfortunately there are large areas of the BC drainage basin that are ungauged. In order to calculate the total runoff for a basin it is necessary to provide estimates for the ungauged areas.

The classic water balance equation is *Runoff = Precipitation – Evaporation,* which can be rewritten as $1 = \frac{R}{P} + \frac{E}{P}$. With observations of runoff and precipitation we calculate the *R/P* ratio at the gauges. If we assume that *E* and *R/P* are constant across the local area, then we can use the *R/P* ratio to estimate runoff R_u for the ungauged portion of the area.

$$R_u = Area_u \bullet P_u \bullet {}^{R}\!/_{P}$$

We divide each drainage basin into "inland" and "coastal". "Coastal" areas are less than 1000 m in elevation and less than 100 km from the coast. Areas above 1000 m or more than 100 km from the coast are considered to be "inland". Here snowfall that accumulates over the winter months (Oct.-Mar.) has to be redistributed over the spring freshet (Apr.-Aug.).

Total inland flow is calculated as the sum of three components:

$$R_m=B+P_m \bullet R/P_m+f(snow)_m$$

B	Base flow – the background flow rate that does not respond to short term precipitation fluctuations.
$P_m \bullet R/P_m$	Response flow – the flow directly tied to rainfall.
$f(snow)_m$	Redistributed flow – the flow attributed to snow accumulation.

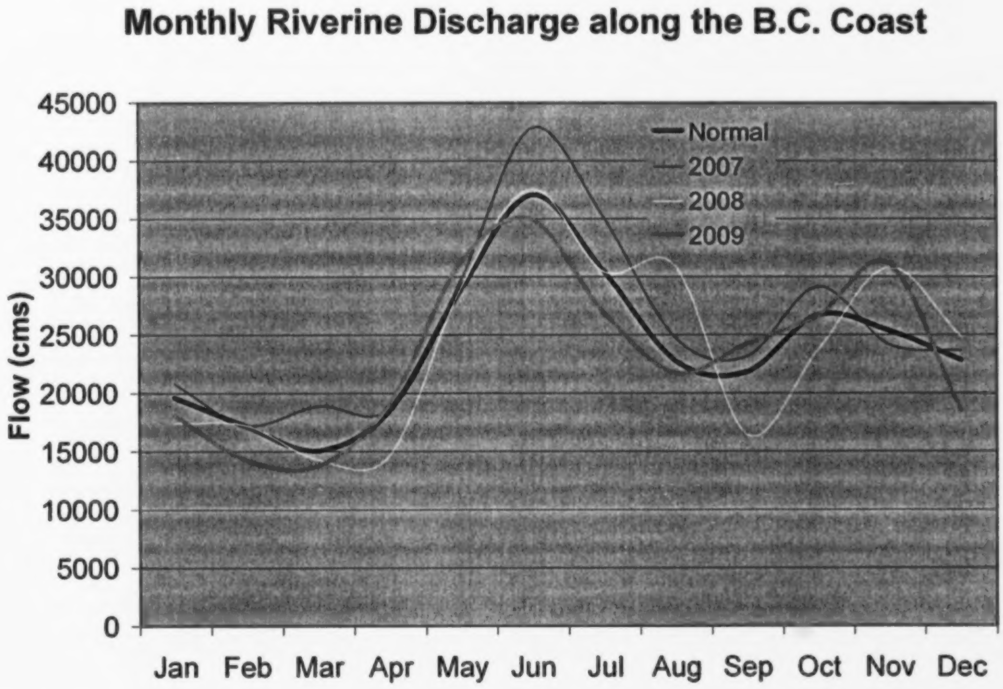
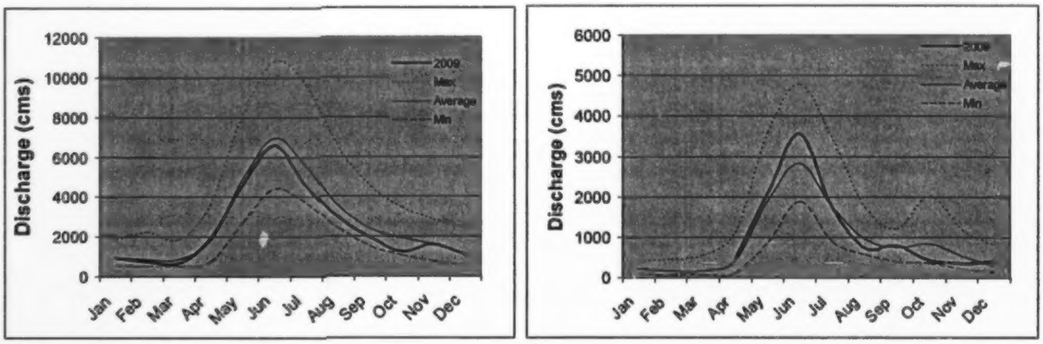


Fig 2. Monthly coastal fresh water discharge. It is dominated by the prominent spring freshet that is due to the melting on the snow accumulation from the province's interior. The secondary peak is the response to the fall rains. 10000 cubic metres per second (cms) = 315.4 km^3 yr^{-1}.

Normal freshwater inflow to the BC coast, calculated using average precipitation and flows, is 753 km^3 yr^{-1}. In 2009 the freshwater inflow was estimated to be 738 km^3 yr^{-1}. Discharge in early 2009 and in June to August was somewhat below average. November discharge was considerably above average due to severe rainfall in this month, but dropped quickly in early December 2009.

Skeena and Fraser River 2009 discharge

The longest continuous discharge record in the Fraser River is at Hope and so, although there are gauging stations below Hope, it has become the de facto standard location for evaluating changes in flow conditions for the Fraser River. In 2009 (Fig 3a) the discharge tracked the long term average for the first half of the year. After the peak of the freshet, discharge dropped below the long term average until late fall when heavy fall precipitation restored discharge to near normal. The Skeena River, as measured at Usk (Fig 3b), also tracked the long term average in the early part of the year but in this case had a very strong freshet about 25% above the normal peak flow level. The secondary fall peak was a month early in 2009 so that October, which normally has high flow, was at near record low flows.



a) *b)*

Fig 3 a) 2009 discharge in the Fraser River as measured at Hope. Minimum, average and maximum flows for the period 1912-2005 are in black. b) 2009 discharge in the Skeena River as measured at Usk. Minimum, average and maximum discharges for the period 1928-2005 are in black. (Note the difference in scale)

Fraser River summer temperatures

River temperatures observed at Qualark were above the long term average from early July through the end of the Sockeye salmon migration forecast season on September 15. The peak temperature was 21.0° C on August 3 which was 3.5° C above the 1942-2009 average for that date. One daily average high temperature record was set at 18.9° C on September 3.

Outlook for 2010

After some record flows in mid January 2010 the Skeena has been at its normal level from February through March. The Fraser has shown a similar pattern with high flow in mid January and with normal flows from February through March. Snow pillows in the Fraser watershed are near the 90% level and there is speculation about low snow accumulation at lower elevations. By April 1 the Skeena snow pillows were at 74% of their normal level. Environment Canada is predicting above-normal temperatures through the spring and early summer. With lower-than-normal water availability and higher-than-normal temperatures it is likely that these rivers will experience elevated temperatures during the Sockeye migration period. This fits the long term correlation (Foreman et al 2001) between El Niño winters and summer Fraser conditions.

Foreman, M. G. G., D. K. Lee, J. Morrison, S. Macdonald, D. Barnes and I. V. Williams, (2001) Simulations and Retrospective Analyses of Fraser Watershed Flows and Temperatures, *Atmosphere-Ocean* 39(2) 89-105.

COOL SUB-SURFACE WATERS IN THE STRAIT OF GEORGIA

Diane Masson, Fisheries and Oceans Canada

The relatively cold conditions prevailing in the Strait of Georgia since mid 2007 and that intensified through 2008 persisted through most of 2009. Figure 1 shows contours of temperature since 2000 measured at the Nanoose station, which is located in the central deep basin of the strait at 49° 18.7'N, 124° 2.7'W). In the spring and early summer of 2009, sub-surface intrusions of colder water lowered temperatures throughout the water column. Sub-surface temperatures remained relatively cold through the rest of the year.

Figure 2 gives the temperature anomalies over the last 10 years at Nanoose relative to the average computed over the period 1971-2000. This shows that from 2000 to mid-2003 temperatures were near the long term-mean, followed by a few years with anomalously warm temperatures. This relatively warm episode ended in the summer of 2007 as the water column returned to near-normal temperatures. Subsequently, cooler conditions became established, with negative temperature anomalies prevailing during 2008 and 2009, particularly in the deep strait. In fact, temperatures of the deep water of the Strait have not been this low since the extreme cold event of 1979 (Masson and Cummins, 2007). Temperatures in the strait are anticipated to rise in 2010 in response to El Niño conditions that developed in the tropical Pacific in 2009.

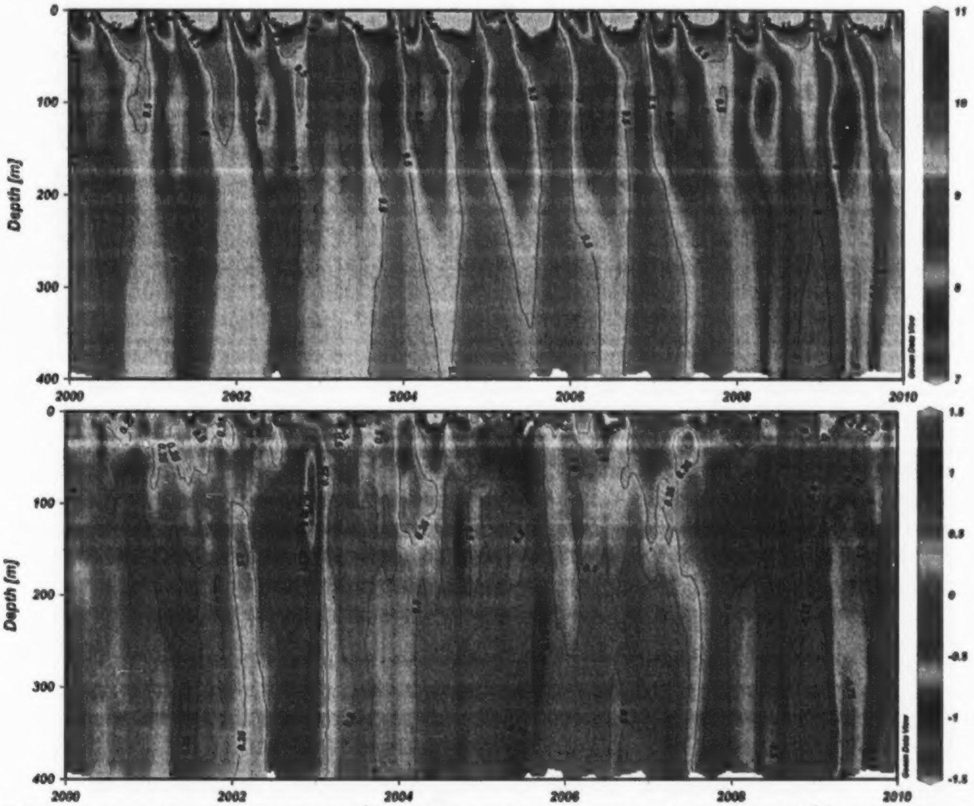


Figure 1: Contours of temperature (°C, upper panel) and temperature anomaly (°C, lower panel) measured at the Nanoose station (central Strait of Georgia) for 2000-2009. Anomalies are computed relative to the mean for 30 year period 1971-2000.

Reference

Masson and Cummins, 2007. Temperature trends and interannual variability in the Strait of Georgia, British Columbia. Continental Shelf Res., 27, 634-649.

VENUS REPORTS CHANGING TEMPERATURE, SALINITY AND OXYGEN AT OCEAN BOTTOM

Richard Dewey, Victoria Experimental Network Under the Sea, University of Victoria

The Victoria Experimental Network Under the Sea (VENUS) is a coastal cabled observatory with arrays in Saanich Inlet and the southern Strait of Georgia. VENUS provides the first and only continuous records of ocean properties below the surface in British Columbia. The Saanich Inlet (SI) array includes a shore station at the Institute of Ocean Sciences and a 3 km cable to a Node at 100 metres depth (("SI" at 48° 39.0540'N 123° 29.2027'W). The Strait of Georgia (SoG) array consists of a shore station at the Iona Waste Water Treatment Plant, a 40 km cable, and two Nodes, one in the central southern strait at 300 metres depth ("SoG Central" at 49° 2.41'N 123° 25.53'W), and a second on the eastern flank at 170 metres depth ("SoG East" at 49° 2.52'N 123° 19.06'W). At each VENUS Node there is a standard VENUS instrument platform (VIP) hosting oceanographic instruments including a CTD to measure temperature and salinity, an ADCP to measure currents, and an inverted echo-sounder to detect zooplankton.

The Saanich Inlet sensors reveal that the winter of 2008/09 continued the cooling trend of 2008, whereas the summer of 2009 was relatively warm, resulting in a rebound of the deep temperatures back to more typical values by late 2009 (Figure 1). In fact, after the winter cooling of 2008/09, temperatures in Saanich Inlet at 100 m were the coolest in the (short) VENUS record (7.5 C), and the summer (May-October) warming was the largest seasonal increase observed in the past 4 years (from 7.5 to 9.5 C). Accompanying the cool spring (April) temperatures were relatively fresh conditions, with the saltiest seasonal salinity minimum (30.6 in April 2009) on record. Salinity maxima values (31.1 in October 2009) were typical compared to previous years. Dissolved oxygen at the VENUS site in Saanich followed a similar trend in 2009 to previous years, with maximum concentrations at 100 m reaching 3.2 ml/l in April, and minimum values reaching 0.05 ml/l in late September, as deep water renewal within the Inlet basin displaces and pushes very low oxygen water upwards passed the VENUS site at 100 m.

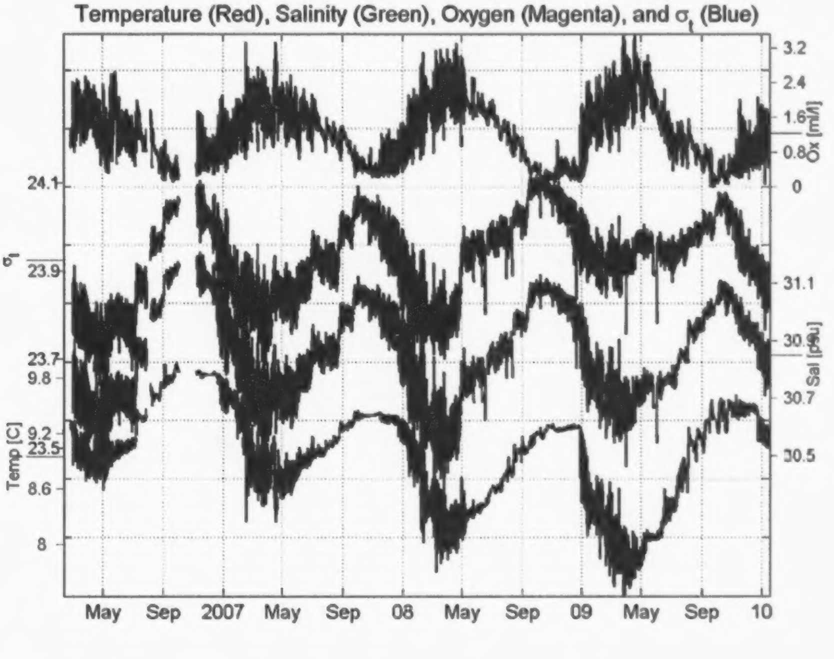


Figure 1. time series of water properties (temperature/red, salinity/green, σ_t/blue) and dissolved oxygen (magenta) from the VENUS Station in Saanich Inlet, located at the mouth of Patricia Bay at a depth of 100 m. Shown are the full VENUS records, from 2006 through to early 2010.

Although analysis of data from the Strait of Georgia by various VENUS users is on-going, there are a few key observations and signals detected in 2009 that emerge clearly. First, the acoustic Doppler current profilers (ADCPs) in the southern central Strait reveal a consistent change of current flow with depth, with stronger northward-flowing currents in the lower half of the water column and stronger southward-flowing currents in the upper water column. This vertical shear is likely due to a buoyancy-driven circulation associated with Fraser River discharge. In general, the super-imposed tides, which also flow mainly North-South, result in deep currents that flow northward during flood but are weak or completely arrested during ebb, and conversely in the upper water column, currents that flow southward during ebb are either weak or completely arrested during flood. Further imposed on these very general characteristics are periodic and more complex events associated with the spring-neap tidal cycle, strong winds, river discharge, internal waves, and deep-water renewal gravity currents.

The CTD and oxygen records from VENUS' two Strait of Georgia stations are shown in Figures 2 and 3. Several key features are evident at each site. Figure 2 presents time series at SoG East at 170 m depth, capturing two annual cycles. All four time series are highly correlated, indicating that there is a tight Temperature-Salinity (T-S) relation, and that dissolved oxygen is also tightly tied to specific water source and formation characteristics. Seawater density (sigma-t = σ_t) is more influenced by salinity, with saltier & denser water coinciding with warmer conditions. Warming and salinity increases are observed from March to September. Winter cooling and freshening is confined between October and March. Dissolved oxygen is anti-correlated with temperature; warmer water having less dissolved oxygen and colder water more dissolved oxygen. Salinity and density have persistent local variations associated with the fortnightly tidal cycle throughout the year, while temperature and oxygen pickup some variability during the summer associated with spring and summer deep-water intrusion events, followed by strong tidal oscillations during the cooling winter months.

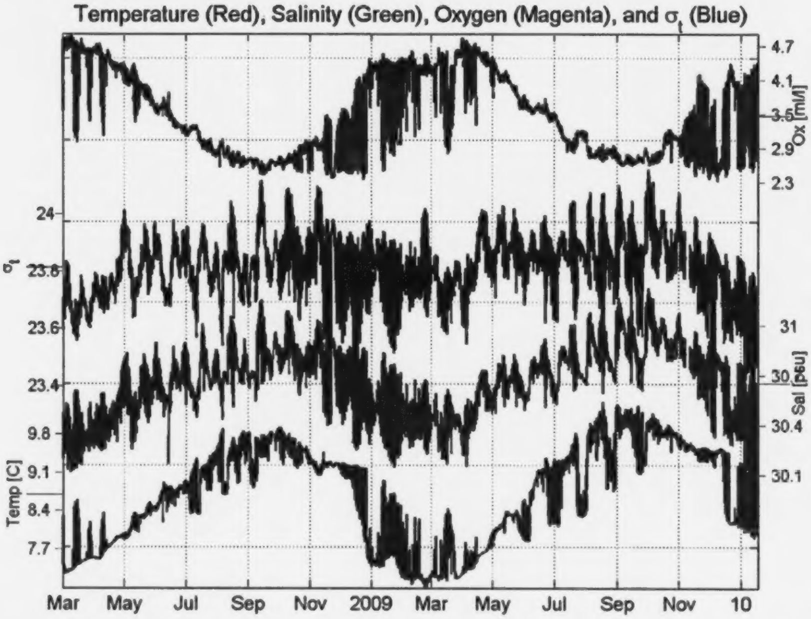


Figure 2. CTD (temperature/red, salinity/green, σ_t/blue) and dissolved oxygen (magenta) from the VENUS Station (SoG East) in south central Strait of Georgia at a depth of 170 m. Shown are the full VENUS records, from February 2008 through to early 2010.

For the deep (300m) VENUS station (SoG Central, Figure 3), the CTD record captures just over one complete annual cycle (September 2008 to January 2010). At this location, along the thalweg from the shallow banks to the south into the deep northern Strait, we see a slightly different salinity variation over the year compared to SoG East. In particular, the temperature (and oxygen) are similar to the records from both Saanich Inlet and the SoG East site at 100 and 170m, respectively, with cooling from late December through to April, followed by warming from May through to November. Superimposed on this temperature cycle are short-duration pulses tied tightly to tidal mixing within the Gulf Islands at spring-neap periods. When the temperature is decreasing, the oxygen is increasing. This is consistent with atmospheric cooling and air-sea gas exchange; whereby surface cooling coincides with injection of gas across the air-sea interface, such that cooler water detected at 300 m is accompanied by higher oxygen associated with atmospheric exchange. Unlike either Saanich (100m) or SoG East (170m), the salinity and temperature are not coupled throughout the year. Although the warming trend starts in May, salinities increase only for short periods during pulses of deep-water renewal, and finally rebound during one three-day period in late September/early October during a single significant deep-water renewal event, long after temperatures have been rising. Strangely, oxygen concentrations reveal no anomaly during this major salinity-driven deep-water renewal in early October 2009 (Figure 3).

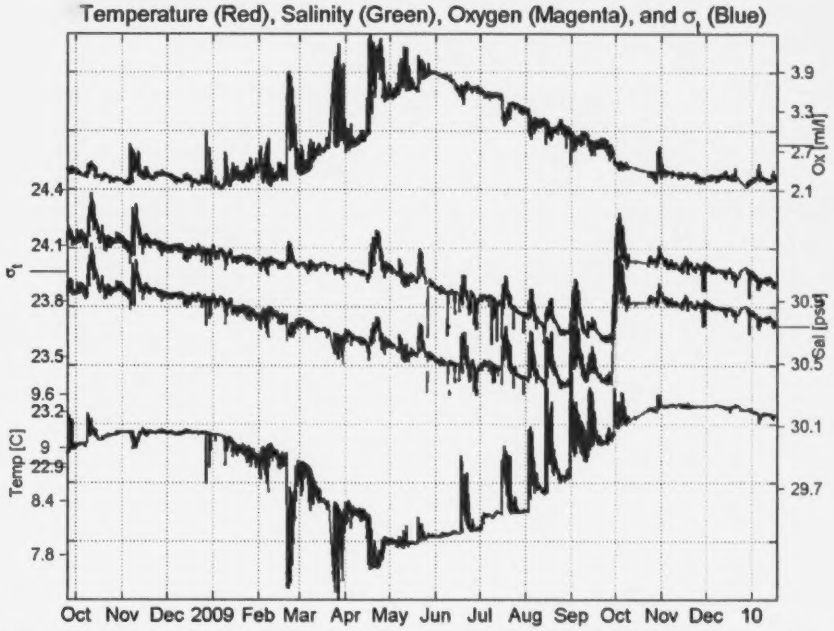


Figure 3. CTD (temperature/red, salinity/green, σt/blue) and dissolved oxygen (magenta) from the VENUS Station (SoG Central) in south central Strait of Georgia at a depth of 300 m. Shown are the full VENUS records, from September 2008 through to early 2010.

Several important annual cycles are revealed in the VENUS time series. Atmospheric cooling and solar heating dominate the seasonal temperature variations. Atmospheric exchange seems to drive annual variations in oxygen concentration, as revealed by these near-bottom data, since oxygen and temperature out of phase. Salinity decreases due to local river discharge in fall and winter, and increases during summer due to inflow of deep, salty Pacific water entering via Juan de Fuca Strait. Deep-water inflows show up as pulses timed to the spring-neap cycle, and are likely forced by vertical mixing and water mass formation within the Gulf Islands. At these depths (100-300 m) the role of the Fraser River appears to be secondary through its ability to drive an estuarine circulation that brings deep, salty Pacific water in through the Gulf Islands.

PHYTOPLANKTON IN JUAN DE FUCA/STRAIT OF GEORGIA

Angelica Peña, Fisheries and Oceans Canada

Phytoplankton and nitrate concentrations are measured seasonally along a 20-station transect in Juan de Fuca / Strait of Georgia Basin (Fig. 1). Chlorophyll concentrations in the Strait of Georgia in April 2009 were the highest so far observed in any survey, reaching concentrations of more than 40 mg m^{-3} in the surface layer (Fig. 2). In comparison, spring chlorophyll concentrations in Juan de Fuca Strait were similar to previous years (less than 3 mg m^{-3}). Chlorophyll is an indicator of phytoplankton biomass, so from these measurements we can estimate the availability of plant food for the entire marine food chain.

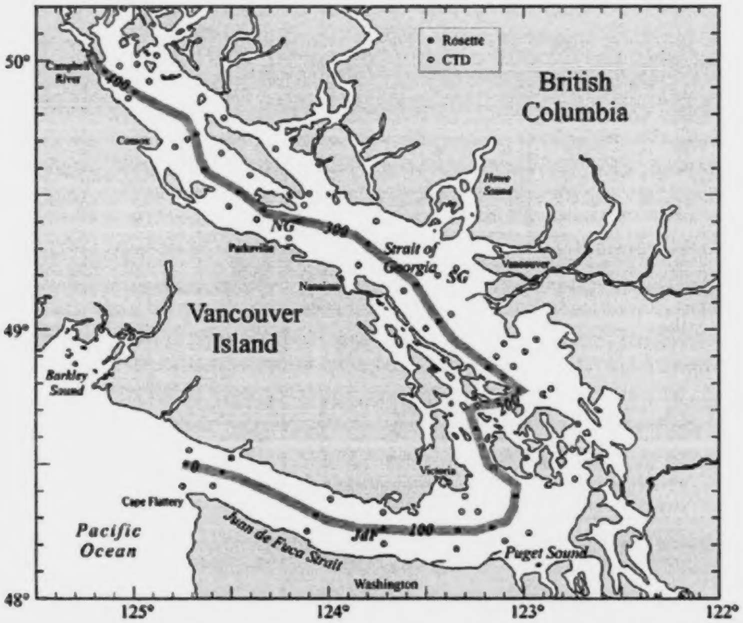


Figure 1: Location of sampling stations in Juan de Fuca Strait/ Strait of Georgia. The thick, shaded line shows the transect of stations used in Figure 2 and 3, with the numbers giving the distance in km from the mouth of Juan de Fuca Strait.

In general, nitrate concentrations are lower and phytoplankton biomass is higher in the Strait of Georgia than elsewhere in this region (Fig. 2). Seasonally, chlorophyll concentrations in the Strait of Georgia are highest during the spring bloom (March-April), low during the summer, increasing again at the end of the summer/early fall, and lowest during winter. In contrast, in Juan de Fuca Strait, chlorophyll concentrations are usually lower than in the Strait of Georgia and remain generally low all year (<3 mg m^{-3}).

In summer 2009, however, upper layer (0-15 m) chlorophyll concentrations in Juan de Fuca Strait were unusually high (> 5 mg m^{-3}) compared to previous years (2002 to 2008), and higher than those measured in the Strait of Georgia (Fig. 2). At the same time, upper layer (0-15 m) nitrate concentrations in Juan de Fuca Strait and at the northern end of the Strait of Georgia were lower than those observed in June of the seven previous years. At other locations, nitrate concentrations were similar to those observed in previous years. During fall of 2009, the distribution of phytoplankton and nitrate concentrations were within the range of values observed in previous years, except at the mouth of the Strait. In winter of 2009, chlorophyll and nitrate concentrations in Juan de Fuca Strait were relatively low compared to those of previous years (Figure 2). Otherwise, the distribution and concentration of chlorophyll and nitrate were within the range of values observed in previous years.

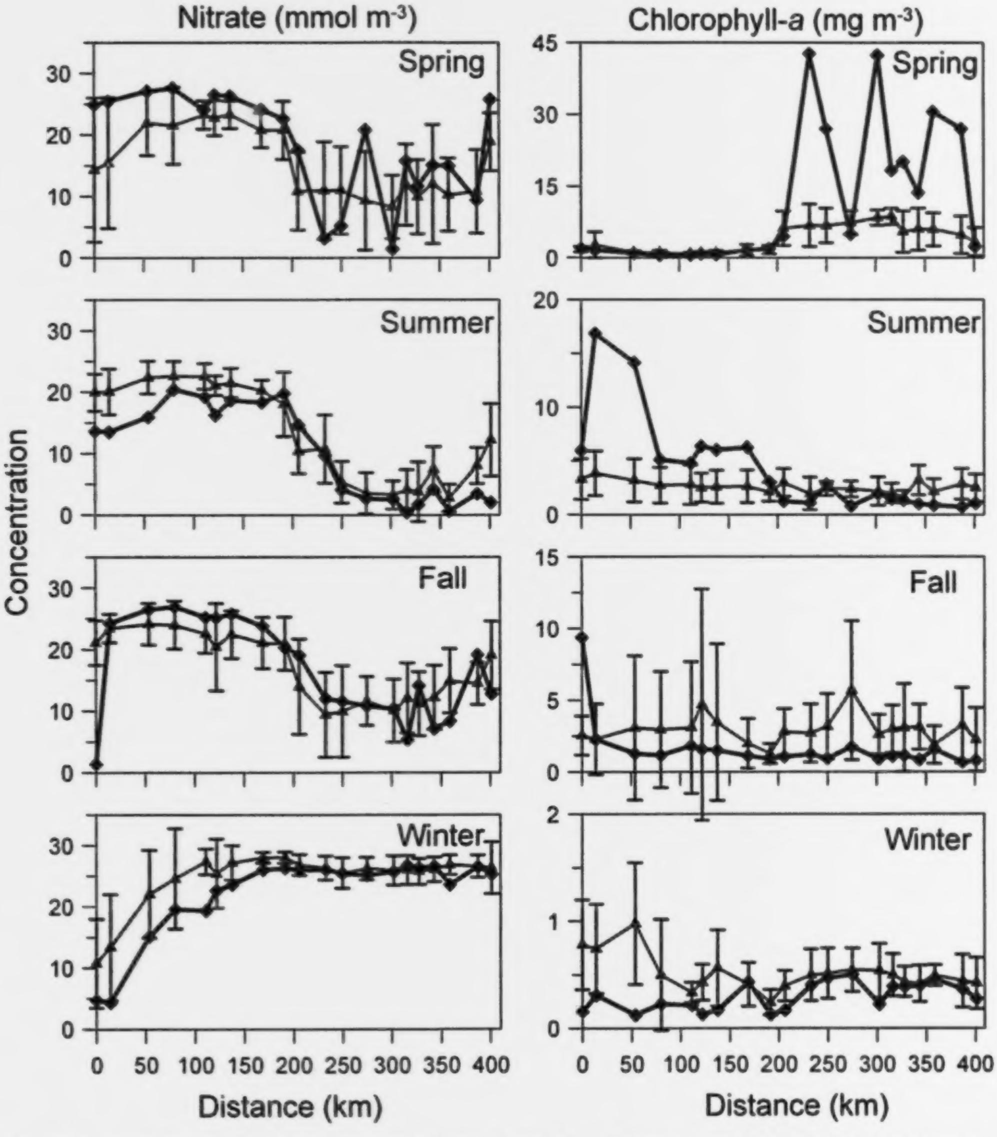


Figure 2. Upper layer (0-15 m) concentrations of nitrate (left panel) and chlorophyll (right panel) along a transect from the mouth of the Juan de Fuca Strait to the north end of the Strait of Georgia during spring, summer, fall, and winter. Blue diamonds are observations in 2009. Grey triangles and bars denote averages and standard deviations from 2002 to 2008 for nitrate and 2004 to 2008 for chlorophyll. Numbers along lower axes are cumulative distance from the mouth of Juan de Fuca Strait (see Fig. 1).

In the spring of 2009, the composition of the phytoplankton assemblage, as determined by high-performance liquid chromatography (HPLC)-derived phytoplankton pigments, was similar to previous years. Fucoxanthin, the biomarker for diatoms (a type of phytoplankton), was the most abundant accessory pigment at this time of the year (Figure 3) as expected during the spring bloom of diatoms in the Strait of Georgia. The unusually high phytoplankton biomass in Juan de Fuca Strait in summer of 2009 was also due to the abundance of diatoms. In this case, the contribution of fucoxanthin to total phytoplankton pigment was higher than those observed in previous summers.

Monitoring changes in phytoplankton composition is at least as important as monitoring changes in biomass since the transfers of phytoplankton production to higher trophic levels are mediated by the assemblage composition of the phytoplankton – diatoms, flagellates, harmful algal blooms.

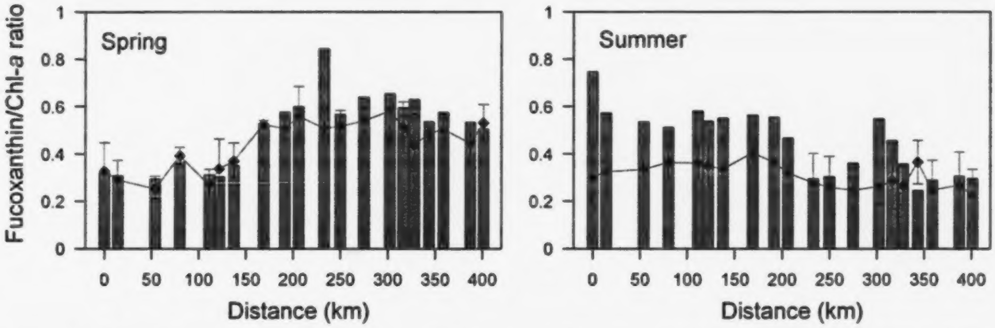


Figure 3. Upper layer (0-15m) distribution of fucoxanthin, normalized to chlorophyll, along a transect from the mouth of Juan de Fuca Strait to the north end of the Strait of Georgia during spring and summer. Grey bars are observations in 2009. Blue diamonds and bars denote averages and standard deviations from 2004 to 2008. Numbers along lower axes are cumulative distance from the mouth of Juan de Fuca Strait (see Fig. 1).

REMOTE SENSING OF CHLOROPHYLL IN THE STRAIT OF GEORGIA

Jim Gower and Stephanie King, Fisheries and Oceans Canada

We use the high spatial resolution of MERIS and MODIS satellite imagery to monitor chlorophyll concentrations along the BC coast. Availability of the higher resolution MERIS imagery (300m) has recently been improved by upgrades to Canadian satellite receiving stations.

In February and March of the years 2001-2009, MERIS and MODIS imagery showed a chlorophyll pattern recurring in three years out of nine, which suggests seeding of the early spring bloom in the Strait of Georgia from deep, glacial inlets to the north. High chlorophyll values are first observed in Jervis and Sechelt inlets in mid-February, then in Malaspina Strait, an arm of the Strait of Georgia, before spreading across the main body of the Strait in late February and early March.

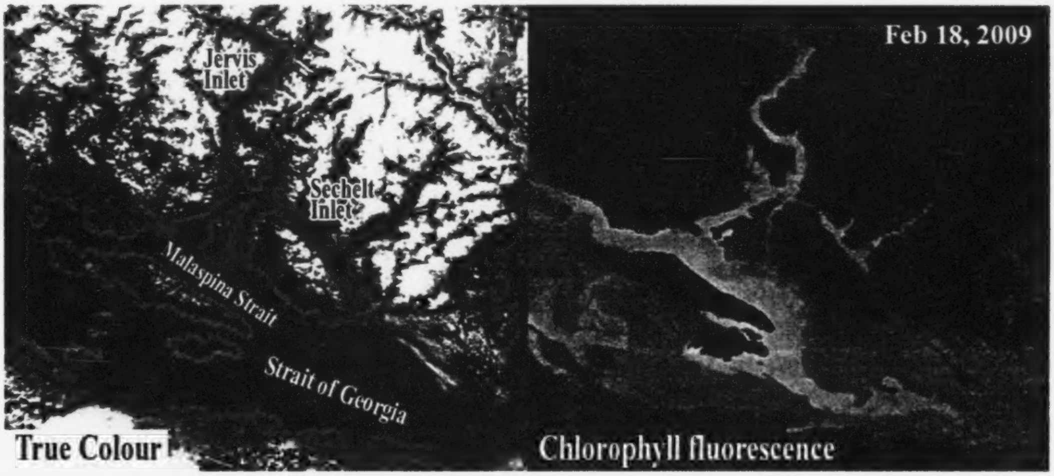


Figure 2. MERIS full resolution (300 m) images for 18 February 2009 for the central Strait of Georgia and Jervis and Sechelt Inlets to the north. The true-colour image (left) shows snow over high elevations on land, cloud cover and a digital coastline. The chlorophyll fluorescence image (right) shows ocean surface chlorophyll, here with the "Malaspina Dragon" pattern due to a bloom from Jervis Inlet entering the Strait. The name derives from its dragon-like shape, with head at lower right, tail at top left. Low chlorophyll values are shown in blue. Higher values are shown in green, yellow and orange. Land and clouds are coloured black.

We call the pattern the "Malaspina Dragon" after its shape in satellite imagery in 2005, 2008 and 2009 shortly after it entered the Strait. It appears that the main spring bloom in the Strait of Georgia occurs earlier in years when the Dragon is present, suggesting that seeding from inlets in some years should be added to the list of factors controlling timing of the main spring phytoplankton bloom in the Strait of Georgia.

These images give the first direct evidence of "seeding from inlets" into the Strait of Georgia. This "seeding" has been suggested in the past as a mechanism for triggering the main spring bloom in the Strait, but potential source regions were unknown. These results suggest a need for improved local monitoring of the timing and spatial pattern of phytoplankton growth in February and March of each year, in Sechelt and Jervis Inlets as well as in the main body of the Strait.

PREDICTION OF THE SPRING BLOOM IN THE STRAIT OF GEORGIA

Susan Allen[1], Megan Wolfe[1] and Doug Latornell[1] with satellite observations from Jim Gower[2]
[1] Earth and Ocean Sciences, University of British Columbia [2]Fisheries and Oceans Canada

Spring blooms in the Strait of Georgia are observed to vary interannually from late February until mid-April. We have developed a one-dimensional coupled biophysical model of the Strait of Georgia and used it to hind-cast spring blooms. It is based on a mixing-layer model (Large et al., 1994) with baroclinic pressure gradients and estuarine circulation added (Collins et al., 2009). The physical model is coupled to a simple, standard, nitrogen-phytoplankton model. The phytoplankton modelled is *Thalassiosira* spp., which is observed to be the first phytoplankton to in the Strait. Physiological parameters are taken from the literature and the model is tuned using the zooplankton biomass. The model accurately hind-casts the spring blooms of 2002-2005 for which detailed observations were made as part of the STRATOGEM project (Collins et al., 2009).

Using this model we have investigated the sensitivity of the spring bloom to physical forcings including wind, cloud fraction, temperature and river run-off. We determined a fit, based on December to February averaged wind speed cubed, cloud fraction and river outflow, to predict the spring-bloom by the end of February. Predictions made in 2006, 2007, 2008, and 2009 were accurate. The enclosed figure shows the predicted blooms with accuracy bounds and observations. The prediction for 2010 is also shown.

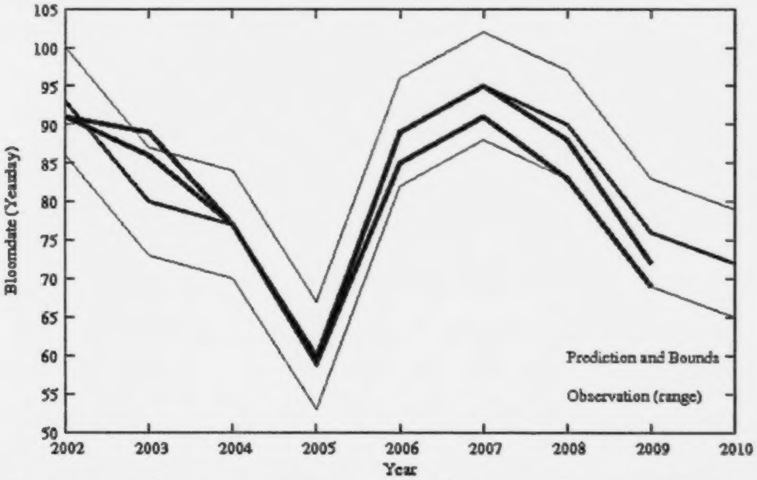


Figure 1. The observed bloom dates are in blue with a range for years where the data were unclear and the predicted bloom dates are in red with a plus/minus 10-day range to reflect the inherent variability due to individual storm events.

In Dec 2009- Feb 2010 our weather has been unusually calm with the weakest winds since 2005. Unlike last year, clouds have been near average. Like last year river flow has been low. Our prediction for the spring bloom in 2010 is March 7 to March 21. Thus we are predicting a 2010 spring bloom with similar timing to 2009. The empirical model does not include temperature effects. Given the record temperatures in January in 2010, it is possible the bloom will be even earlier.

References

Collins, A. K., S. E. Allen, and R. Pawlowicz, The role of wind in determining the timing of the spring bloom in the Strait of Georgia. *Can. J. Fish. Aquat. Sci*, 66, 1597-1616, 2009.

Large, W. G., J. C. McWilliams, and S. C. Doney, Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, 32(4), 363–403, 1994.

SMALL PELAGIC FISHES IN THE STRAIT OF GEORGIA

Jake Schweigert and Jaclyn Cleary, Fisheries and Oceans Canada

The report focuses on Pacific herring for which ongoing data collection and monitoring occurs. An egg and larval survey continues for eulachon within the Fraser River and indicates that this population remains at critically reduced abundance.

Herring survival conditions and recruitment have been unusually good in the Strait of Georgia for the last decade. Abundance of herring reached near historical high levels from 2002-2004 exceeding 100,000 tonnes. Weaker recruitment of the 2003 and 2005 year-classes resulted in a substantial decline in abundance in recent years. Recruitment of a strong 2006 year-class in 2009 has halted the decline and resulted in a slight increase in abundance.

The Pacific herring stock in the Strait of Georgia migrates inshore in the fall and leaves the Strait for the west coast of Vancouver Island in the spring following spawning. Survival conditions for juvenile herring in the Strait of Georgia have been unusually good during the last decade. Abundance of herring in the Strait of Georgia reached near historic high levels from 2002-2004 at over 100,000 tonnes (Figure 1). Recruitment to this stock has been very strong with 9 of the last 10 year-classes being average or better (Figure 1). The strongest recruitment occurred in 2002 and subsequent year-classes have been progressively smaller with the exception of the 2004 and the recently recruited 2006 year-class. Juvenile rearing conditions within the Strait of Georgia appear to be an important determinant of recruitment success for this stock since most juveniles do not leave the area until their second summer. Initial indications are that the recruitment in 2010 should be weak based on surveys of juvenile abundance and could limit recent increases in overall abundance.

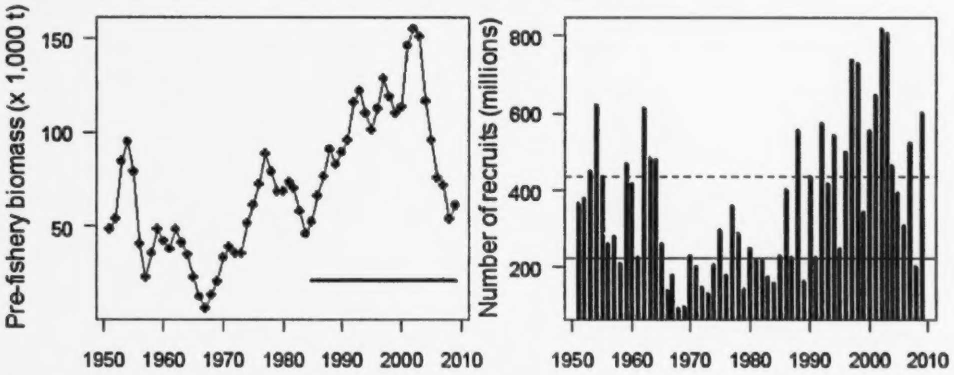


Figure 1. Interannual variability and decadal trends in abundance (left) and recruitment (right) to the Strait of Georgia herring stock. Left figure: solid horizontal line denotes commercial fishing cutoff. Right figure: boundary for 'poor'- 'average' recruitment indicated by solid line; boundary for 'average'- 'good' recruitment indicated by dashed line.

Interpretation and speculative results

The abundance of the Strait of Georgia herring stock in 2009 rebounded slightly from the decline that began in 2002 from the near historic high levels of more than 100,000 tonnes. The reduced recruitment over the past five years will impact the mature abundance levels over the next few years. Fall surveys of juvenile herring suggest a poor recruitment in 2010 followed by an average year-class in 2011.

FRASER RIVER SOCKEYE SALMON PRODUCTIVITY AND 2010 RETURN FORECASTS

Sue Grant[1] and Catherine Michielsens[2]
[1]Fisheries and Oceans Canada [2]Pacific Salmon Commission

Sockeye salmon returns are forecast annually for 19 Fraser River stocks with escapement and recruitment data. The models used each year are those that retrospectively generated forecasts with the least bias and highest precision.

For the previous year's (2009) forecast, returns were below the 10% probability level (Figure 1). In generating the 2009 forecast, long-term average productivities had been assumed, which seemed reasonable given that marine indicators suggested that conditions for salmon survival would be relatively good (see p. 117 Crawford & Irvine 2009). Chilko marine survival had coincidentally increased for the 2004 brood year (2006 ocean entry and 2008 returns) relative to the 2003 brood year (DFO 2009). Therefore, these indicators did not predict the low marine survival for Fraser Sockeye salmon that went to sea in 2007; separate work is examining the potential utility of other indicators that may be more appropriate.

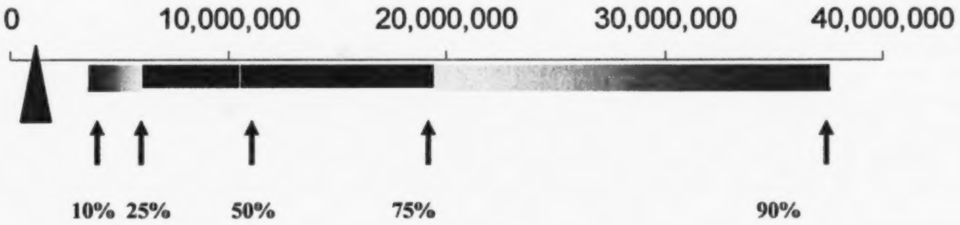


Figure 1. The 2009 total forecast probability distributions (indicated by blue arrows) for all Fraser Sockeye Salmon Stocks and 2009 preliminary returns (red triangle). Black horizontal bars represent the 25% to 75% probability distribution range with the 50% probability level indicated by the white vertical line and the blue (lighter) horizontal bars represent the 10% to 90% probability distribution range.

For the 2005 brood year (2007 ocean entry and 2009 returns), productivity was amongst the lowest on record for most Fraser Sockeye stocks. Harrison River Sockeye salmon also experienced the lowest productivity on record in the 2005 brood year, despite having a different ocean entry year (2006 ocean entry and 2008/2009 returns) from other Fraser Sockeye stocks from the same brood year. The 2006 brood year productivity for Harrison Sockeye, with the same ocean entry year (2007) as all other Fraser Sockeye that returned in 2009, were below average but improved relative to the 2005 brood year. Harrison Sockeye salmon have an unusual age structure and life history. They are age-3 (3_1) and 4 (4_1), migrating to sea shortly after emergence. Most Fraser Sockeye age-4 (4_2) and 5 (5_2) fish spend a full year rearing in lakes prior to ocean migration.

Fraser Sockeye salmon productivities were estimated with Kalman filtered (KF) Ricker *a* parameters, which describe long term systematic trends in $\log_e$(recruits-per-spawner) (Dorner et al. 2008). Since the 1960's, KF Ricker *a* annual parameter values decreased for 13 of 17 stocks (Cultus and Scotch were not included in this assessment) (Figure 2). Three stocks, including Raft, Late Shuswap and Weaver have not exhibited systematic productivity trends (Figure 2). For these three stocks, all variability in $\log_e$(recruits-per-spawner) was attributed by the KF Ricker model a parameter values to short-term variability (noise) rather than long-term systematic trends (signal) (Dorner et al. 2008). Late Shuswap is expected to dominate returns in 2010. Harrison Sockeye have increased in productivity (Figure 2).

2010 returns were forecast under three different survival scenarios: "Long-Term Average Productivity", "Recent Productivity (brood years: 1997-2003)", and "Productivity Equivalent to the 2005 Brood Year (2009 poor returns)". For each scenario, uncertainty attributed to stochastic (random) variability in annual survival rates is communicated through a series of forecasted values that correspond to standardized cumulative probabilities (10%, 25%, 50%, 75%, 90%). For example, there is a one in four chance at the 25% probability level that the actual number of returning Sockeye will be at or below the forecasted value given the assumptions about future survival.

Out of the three forecast cases listed above, the forecast with the greatest degree of belief (as recommended by the March 9, 2010 Canadian Science Advisory Secretariat (CSAS) Regional Advisory Process (RAP)) was the "Recent Productivity" forecast. For 2010, this forecast assumes that recent productivity will persist through to 2010. Based on this assumption, the number of returning Fraser Sockeye in 2010 will range from 7.0 million to 18.3 million (25% to 75% probability levels) (Figure 3). Sibling (jack) forecasts were produced to compare with models selected for the 2010 "Recent Productivity" forecasts, despite sibling models having the widest probability distributions (greatest uncertainty) of all forecasts. This is particularly relevant for Late Shuswap Sockeye salmon expected to dominate returns in the "Recent Productivity" forecasts for 2010. The sibling model forecast is similar for Late Shuswap (age-4 recruits: 6.3 million) relative to the "Recent Productivity" forecast (age-4 recruits: 7.3 million). For Chilko Sockeye salmon, also expected to contribute a relatively large number of returns to the total "Recent Productivity" forecast (age-4 recruits: 1.9 million), the sibling model also produced a similar forecast (age-4 recruits: 1.2 million) (Grant et al. 2010).

The "Long-Term Average Productivity" forecast ranged from 8.4 million to 23.5 million (25% to 75% probability levels) (Figure 3). The total forecast does not deviate significantly from the "Recent Productivity" forecast because "Recent Productivity" forecast abundance is dominated by Late Shuswap (Late Run) that has not exhibited systematic declines in productivity compared to other stocks (Figure 2). The "Productivity Equivalent to the 2005 Brood Year" forecast ranged from 1.6 million to 7.9 million (25% to 75% probability levels) (Figure 3). This forecast is considerably lower than the "Long-Term Productivity" forecast given productivity in the 2005 brood year (2009) return year was amongst the lowest on record for many stocks (Figure 3).

References

Crawford, W.R. and Irvine, J.R. 2009. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/022. vi + 121 p.

DFO. 2009. Pre-season run size forecasts for Fraser River sockeye and pink salmon in 2009. DFO Can. Sci. Advis. Rep. 2009/022.

Dorner, B., Peterman, R.M., & Haeseker, S.L. 2008. Historical trends in productivity of 120 Pacific pink, chum, and sockeye salmon stocks reconstructed by using a Kalman filter. Can. J. Fish. Aquat. Sci. 65: 1842-1866.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J. & Cass, A. 2010 (in review). Pre-season run size forecasts for Fraser River Sockeye salmon in 2010. Can. Sci. Advis. Sec. Res. Doc. 2010/nnn.

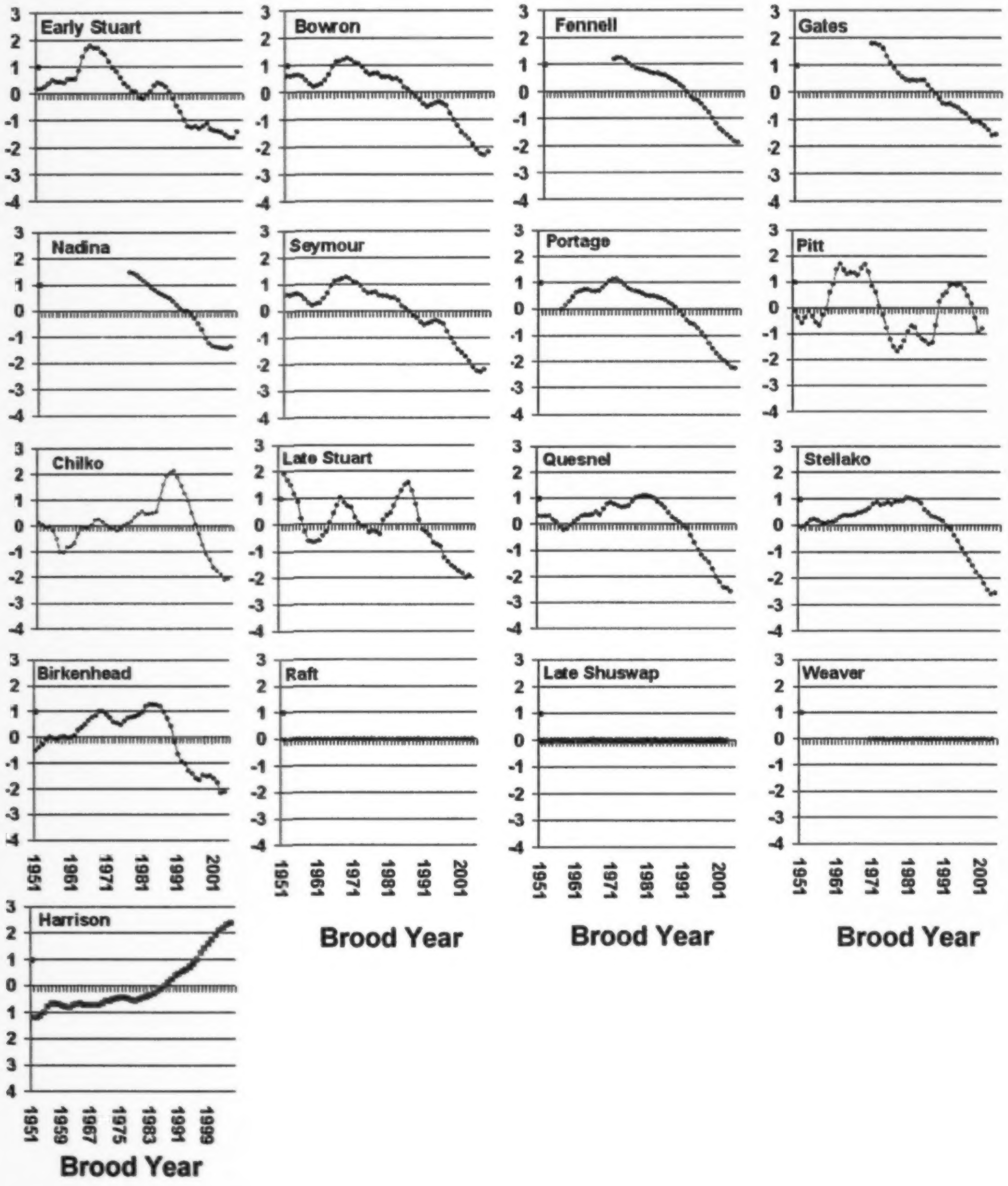


Figure 2. Time series of productivity (Kalman filtered annual Ricker [stock-recruitment model] a parameter values) estimates for each of 17 stocks (Cultus and Scotch excluded), scaled to a mean of zero and a standard deviation of one for stocks with long term productivity declines (red circles), stocks without declines (green diamonds), and the Harrison stock that has increased (light blue squares). The Kalman filter approach describes systematic long-term trends in productivity rather than short term variability in productivity (Dorner et al. 2008). Base code from Dorner et al. 2008.

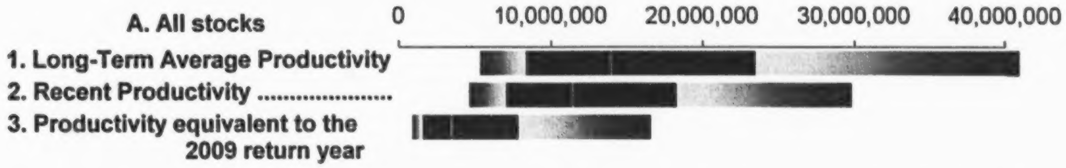


Figure 3. Fraser Sockeye 2010 Forecast probability distributions for three forecast methods that vary based on their assumptions regarding productivity associated with 2006 brood year (2010 returns): 1. Long-Term Average Productivity (uses DFO 2009 methods and model ranks); 2. Recent Productivity (incorporates recent declining productivity into the forecast methods); 3. Productivity Equivalent to the 2005 brood year (2009 return year). Black horizontal bars represent the 25% to 75% probability distribution range with the 50% probability level indicated by the white vertical line and the blue (lighter) horizontal bars represent the 10% to 90% probability distribution range.

POST ARRAY-BASED MEASUREMENTS OF COASTAL OCEAN SURVIVAL OF JUVENILE SALMON, 2006-2009

David W. Welch, Kintama Research Corporation

Description of the POST array

The Pacific Ocean Shelf Tracking (POST) telemetry array is a pilot-scale project to establish the utility of a large-scale marine array for directly measuring the survival and movements of juvenile Pacific salmon directly in large rivers and the coastal ocean (Fig. 1).

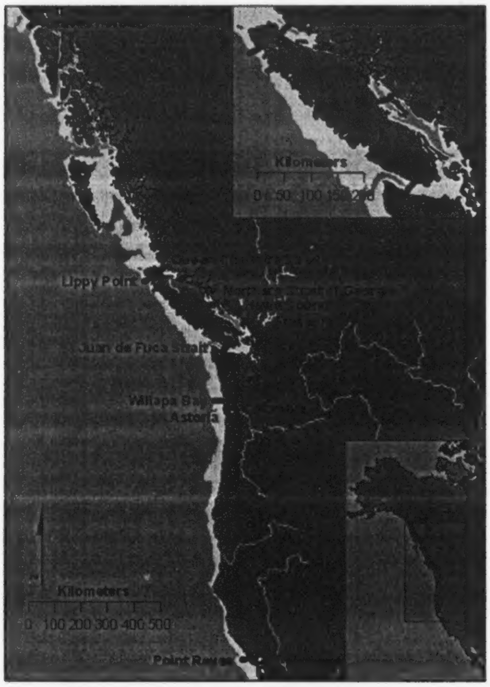


Figure 1. Location of the POST pilot-phase telemetry array (sensor locations indicated in purple). Columbia River spring Chinook salmon migrate north to Alaska along the outer coast, west of Vancouver Island, allowing a measurement of "outer coast" marine survival over 600 km from Willapa Bay, WA to Lippy Point on NW Vancouver Island; Cultus Lake Sockeye migrate primarily via the inside passage through northern Strait of Georgia and Queen Charlotte Strait (denoted the "northern route"), allowing a measurement of marine survival over about 400 km

Salmon are tracked with a prototype freshwater and marine telemetry array formed from a network of individual acoustic sensors positioned within major rivers and the west coast continental shelf. These sensors are used to measure the movements and survival of juvenile salmon, each of which is surgically implanted before release with a uniquely coded acoustic transmitter ("tag"). By reconstructing the movements of each individual salmon from the data recorded by the array, it is possible to estimate survival.

The overall west coast array consists of all receivers from which data have been contributed to the publically-accessible POST database, which includes *ad hoc* receiver placements from which it is generally not feasible to derive reliable survival estimates. This report focuses only on the major core components of the array, which were designed and deployed by Kintama, because statistically accurate and precise survival measurements can be derived from these components.

As part of this effort, Kintama made survival measurements for two stocks of Columbia River spring Chinook salmon as they migrated north from Willapa Bay along the outer continental shelf off Washington State and southern BC to Lippy Point in NW Vancouver Island, from 2006-2009. We have also made similar measurements for young Cultus Lake Sockeye salmon migrating down the Fraser River and out of the Strait of Georgia, including the crucial 2007 smolt outmigration year which led to extremely low returns in 2009 (Welch et al. 2009; a description of the survival measurements for the Columbia River Chinook stocks for 2006 can be found in Rechisky et al. 2009). We used the POST array to measure the survival of freely migrating smolts over extended time periods (up to 3 months post-release, which is the time for the Columbia River Chinook to reach Alaska). Here we focus on the utility of these measurements as a predictor of annual salmon survival levels in southern BC waters and relate them to the independent oceanographic measurements reported in this document.

Outer coast survival (Columbia River Chinook)

Figure 2 compares annual survival estimates of two populations of hatchery-reared Columbia River spring Chinook surgically implanted with POST acoustic tags with independent survival estimates of the same stocks made by NOAA Fisheries (Snake River stock) and Yakama Indian Nation Fisheries (Yakima stock; D. Fast, pers. comm.) using PIT tags. (PIT tags are much smaller and can be injected into the body cavity of the smolt without surgery).

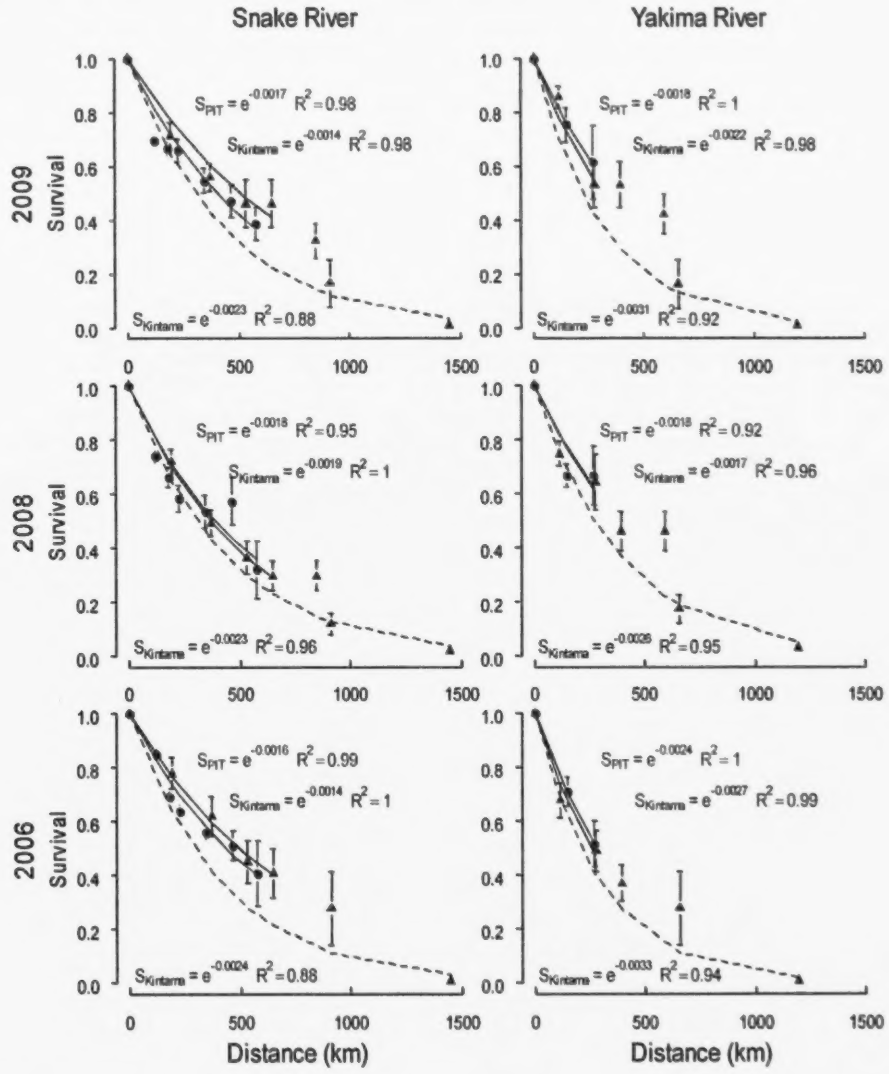


Figure 2. Comparison of independent estimates of down-river survival for two Columbia spring Chinook populations using acoustic and PIT tags (blue and red lines, respectively). PIT tags, small radio-frequency tag detectable at many Columbia River dams, give survival estimates almost indistinguishable from acoustic tags where comparisons are possible. Outer coast survival measurements from Willapa Bay, Wa, to Lippy Point, BC, are shown as the two last (most distant) data points in each panel.

As these two survival estimates are almost indistinguishable over the duration of the freshwater migration where survival can be compared (about 3 weeks after release for Snake River smolts), they provide some independent verification that the acoustic-tag-based estimates of survival are reasonable and that the surgical implantation process is not significantly impairing survival. The results also provide evidence that tag-induced mortality rates are only a relatively small component of the total mortality being measured (see also Rechisky and Welch 2010).

Our acoustic tag survival estimates can be extended to Lippy Point on NW Vancouver Island, and show continuing decline in survival with distance, but with higher losses in the ocean; this is seen in the lower rate of survival evident when the survival model is fitted to both freshwater and marine survival measurements (dashed lines in Fig. 2). When annual survival estimates are calculated by migration segment, hydrosystem survival (survival through the section of the Snake and Columbia rivers containing eight hydroelectric dams), normalized to a constant time period, is constant over the 3 available years (orange bars in lower panel of Figure 3). In contrast, coastal ocean survivals for the Washington and outer BC coasts are much more variable (see also Greene et al 2009).

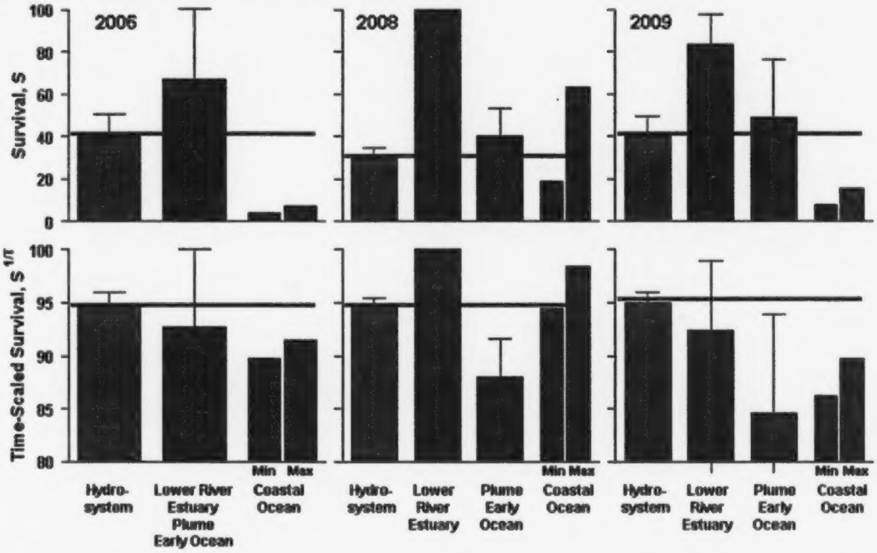


Figure 3. Comparison of Snake River Chinook survival in the Columbia River 8-dam hydrosystem (orange), undammed lower river to Astoria (green), plume (red), and coastal ocean survival from Willapa Bay to Lippy Point on NW Vancouver Island (two blue bars)). The upper row shows survival, the lower row survival scaled per day. .

Because of the limited number of tagged smolts reaching the Alaskan sub-array at Graves Harbor, standard Cormack-Jolly-Seber likelihood-based estimates of survival for the coastal ocean are not possible because we do not have independent data on the detection performance of the Lippy Point sub-array. As a result, we have bracketed the likely detection performance for the acoustic tags used in different years (90% in 2006; 70% in 2008-09) by assuming that this array operated at 50% and 100% efficiency and dividing the numbers detected at Lippy Point by these values to determine the minimum and maximum survival in the coastal ocean (blue boxes). The results show that the estimate of detection efficiency used has relatively little effect on the marine survival measurements.

The exceptional continental shelf ocean conditions observed in 2008 (colder waters, richer and more abundant plankton populations; see sections by Batten and Mackas in this and the previous State of the Ocean report) relative to 2006 and 2009 are mirrored in the Chinook survival rates we measured and plotted in Fig. 3. Unfortunately, we do not have reliable juvenile salmon survival data for the outer coast in 2007 (Porter et al 2009).

Summary for Columbia River Chinook outer coast survival

Measurement of 2008 juvenile Chinook salmon survival indicates that high ocean survival occurred in the coastal ocean from southern Washington to northern Vancouver Island. This direct measurement of coastal survival matches the observations by Trudel (this report) of high catch-per-unit effort of juvenile Chinook along the west coast of Vancouver Island in June to July of 2008. These catch rates in 2008 were the highest in his 12-year time series. These two independent observations suggest high adult Chinook salmon returns in 2010 are likely for salmon stocks that spend significant time as smolts off the west coast of Vancouver Island. The POST 2009 Chinook smolt survival rates were lower for this region, and similar to those measured in 2006, suggesting adult Chinook returns in 2011 will be lower than in 2009.

Cultus Lake Sockeye

Survival of Cultus Lake (Fraser River) Sockeye smolts was previously reported for the 4-year period 2004-2007 (Welch et al. 2009); we summarize the results here in the context of the low returns in 2009 of almost all runs of Fraser lake-type Sockeye (including Cultus Lake), which occurred after Welch et al. (2009) was published. The 2007 Chilko smolts formed the basis for the low 2009 adult run, when the surviving smolts returned as 4 year old adults.

Most of the 200 tagged Cultus smolts in 2007 migrated north via the Strait of Georgia and Queen Charlotte Strait, denoted the northern route (Figure 4), and overall survival in 2007 from release at Cultus Lake to arrival at the north end of Vancouver Island was 27.1% (SE=±3.9%), as high or higher than in the three preceding years of study (Welch et al. 2009). When divided into migratory segments, the same conclusion holds, with the segment-specific 2007 survivals similar to or higher than in preceding years (Figure 5; see Welch et al. 2009 for details). Only 6 tagged smolts were detected emigrating via Juan de Fuca Strait (southern route), of which two (1/3rd) subsequently reached the Lippy Point sub-array. Although not shown in Figure 5, this survival rate for the outer coast is roughly consistent with that seen for the Strait of Georgia/Queen Charlotte Strait migration route. Our data thus provides some limited evidence that, as with Columbia River Chinook survivals in 2006, 2008, and 2009, survival along the outer coast off Vancouver Island remained high in 2007.

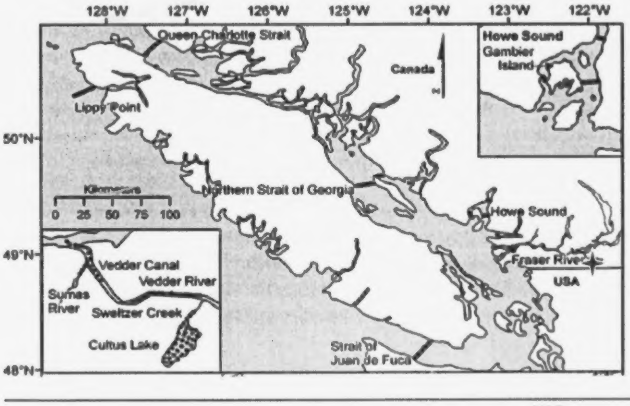


Figure 4. Close up of the acoustic array used for measuring survival of Cultus Lake Sockeye. The release site at Cultus Lake in the lower Fraser River is indicated by a red star and the array components used to measure outmigration survival are labelled. In each year the majority of smolts exited via the inside passage, denoted as "northern route". As a result, survival can be partitioned into three segments; release to mouth of the Fraser River, Strait of Georgia, and Johnstone Strait/Queen Charlotte Strait.

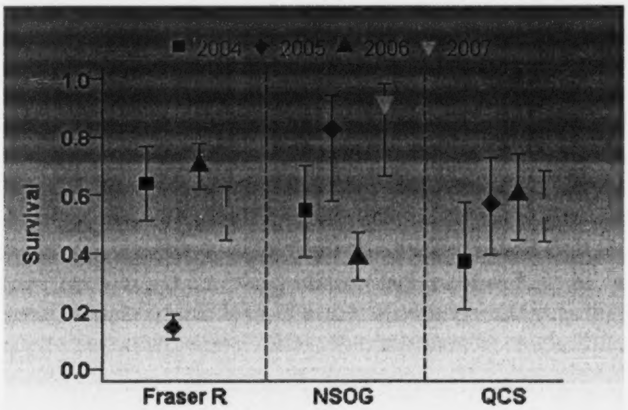


Figure 5. Cultus Lake Sockeye survival by outbound migration segment. NSOG: survival from the mouth of the Fraser River to the north end of Texada Island; QCS: survival from Texada Island through Johnstone and Queen Charlotte Straits to just north of Port Hardy. Error bars indicate 95% confidence intervals on the maximum likelihood estimates of survival (See Welch et al 2009).

Subsequent to the publication of the Welch et al. (2009) results, two adult Cultus Lake Sockeye were detected migrating back to Cultus Lake via the West Coast/Juan de Fuca telemetry sub-arrays in August and early September 2009. All smolts tagged in 2007 were implanted with specially programmed acoustic tags that were activated on 13-14 May 2007, and their acoustic transmissions were turned off on 27-28 June 2007 to conserve battery power. The tags were programmed to begin transmitting their unique ID codes again on 26-27 July 2009 at the expected time of adult return, and to run to battery depletion.

In 2009, one of these tagged adult Sockeye was detected on the Lippy Point sub-array. At the Juan de Fuca sub-array this tag plus one additional tag were detected within a day of each other and both were then subsequently recorded moving up the Fraser River sub-array to as far as Mission (just below Cultus Lake), which is the farthest upstream receiver maintained in the Fraser River by Kintama. The in-bound migration timing to the Strait of Georgia was near the end of August and both adults entered the Fraser River and rapidly moved upstream with little apparent delay in the Strait of Georgia (7 September 2009). The animals' behaviour thus fit with the early river-entry behaviour that the late-run stocks exhibited since 1996 (Cooke et al 2008). It is unknown whether they successfully spawned after passing Mission.

The observed smolt-to-adult survival rate in 2007 to 2009 for the tagged Cultus smolts (2 of 200 tagged smolts, or 1.0% ±0.7% (mean ± 1SE)) is also consistent with preliminary estimates of the survival rate of both wild (1.4%) and hatchery (0.54%) Cultus Lake Sockeye smolts enumerated at the Cultus Lake fence in 2007 and returning in 2009 as adults (M. Bradford, *pers. comm.*). As a consequence, it is possible for the first time to provide an initial "whole life cycle" survival estimate for this salmon population:

Approximately 1% of Cultus Lake smolts survived to return in 2009 (consistent with the survival of most Fraser River populations), so for the equation to balance (assuming 27.1% ≅ ¼):

Overall Survival to Adult Return (1%)	=	*Smolt survival (Migration to QCS)*	x	*Remaining Survival (Migratory survival after initial 1.5 months of life at sea)*

or,

1/100 Smolt to Adult Survival	=	*1/4 Fraser R, Strait of Georgia, & Queen Charlotte Strait Survival (27.1%)*	x	*1/25 (Remainder of Ocean Survival)*

Thus, if roughly 1 in 4 tagged smolts survived to leave the "Salish Sea" ecosystem (equivalent to the 27.1±3.9% survival measured for the Fraser River, Strait of Georgia, and Johnstone/Queen Charlotte Strait segments of the migration path in 2007) then only 1 in 25 of these survivors must survive to yield the observed 1% survival rate of both the tagged Cultus Lake smolts.

Mortality "beyond" the Fraser River/Strait of Georgia ecosystem must be more than 7 times the total mortality encountered in the initial ca. 6 weeks of migration post-release to balance the equation, as demonstrated by the ratio of the initial to subsequent survival rates:

$$\frac{{}^{27.1}/_{100}}{{}^{1}/_{27.1}} \approx \frac{27.1^2}{100} \approx 7.3$$

Thus approximately 7.3 times as much mortality was experienced after the Cultus Lake Sockeye smolts passed out of the Queen Charlotte Strait region than occurred in the first 1.5 months of migration. (No tagged smolts were detected in Alaska, which was as expected because the 2007 tags would have ceased transmitting before the smolts could reach that sub-array).

Our results indicate that there is ample scope for a major mortality event to occur after passing through Queen Charlotte Strait for the Cultus Lake population, and a major mortality does not seem to have occurred within the Strait of Georgia system in 2007. Our data would in fact indicate that Cultus Lake juvenile Sockeye survival in 2007 in the Strait of Georgia/Queen Charlotte Strait ecosystem was good-to-excellent when compared to prior years.

The 1% (2/200) return of adult Cultus Lake Sockeye is consistent with the overall smolt-to-adult survival rate of most lake-type Fraser Sockeye populations returning in 2009 (see Grant and Michielsens, this report). Although acoustic tagging of other Fraser River Sockeye populations has not been done to date, the similar smolt-to-adult survival rates of these stocks in 2009 when compared with the Cultus Lake population suggests that the conclusion for Cultus Lake Sockeye may plausibly be extended to these populations as well. Unfortunately, similar tagging work was not conducted in 2008-2010.

Therefore, the 2009 Fraser Sockeye collapse may have been caused by mortality occurring beyond the Fraser R/Strait of Georgia ecosystem. As the smolts rapidly migrated out of the Queen Charlotte Strait ecosystem, this does not preclude the possibility that, for example, disease contracted during their migration subsequently reduced their survival, but the available data cannot be used to directly support this theory either.

Summary for Cultus Lake Sockeye smolts

Irvine et al (this report) hypothesize that unusually low chlorophyll levels in Queen Charlotte Sound during April 2007 may have resulted in prey for young Sockeye being of low abundance or low nutritional quality when Sockeye migrated through the area about two months later, causing low marine survivals for Fraser Sockeye salmon returning in 2009. Our data indicate that in 2007 Cultus Lake Sockeye smolt survival during outmigration prior to reaching Queen Charlotte Sound was high relative to prior years in both the Fraser River and in the Strait of Georgia/Johnstone Strait/Queen Charlotte Strait regions (27.1±3.9%; estimated overall survival ±1SE; Welch et al. 2009) and that total mortality experienced after the Cultus Lake Sockeye smolts passed beyond Queen Charlotte Strait was estimated to be at least seven times the mortality experienced to that point.

Therefore, the 2009 Cultus Lake Sockeye adult run failure may have occurred because of events occurring after the first month in the ocean and beyond Queen Charlotte Strait, consistent with Irvine et al's hypothesis. Only 1% of these tagged smolts survived to return in 2009 as adults (2 fish returning out of 200 tagged in 2007, a similar survival rate as for other lake-type Fraser River Sockeye runs in 2009). Because the Cultus and overall Fraser River survival rates are similar, it is plausible that other Fraser River Sockeye smolts in 2007 also had greater mortality after migrating through Queen Charlotte Strait. This inference assumes that the Cultus Lake population is representative of other Fraser River populations and the 1±0.7% (average ±1SE) return rate of acoustically tagged Cultus Lake smolts is a meaningful sample.

References

Cooke, S.J., S.G. Hinch, A.P. Farrell, D.A. Patterson, K. Miller-Saunders, D.W. Welch, M.R. Donaldson, K.C. Hanson, G.T. Crossin, M.S. Cooperman, M.T. Mathes, A.G. Lotto, K.A. Hruska, I. Olsson, G.N. Wagner, R. Thomson, R. Hourston, K.K. English, S. Larsson, J.M. Shrimpton, and G.V.d. Kraak. (2008) Developing a mechanistic understanding of fish migrations by linking telemetry with physiology, behaviour, genomics and experimental biology: an interdisciplinary case study on adult Fraser River sockeye salmon. *Fisheries* 33:321-338.

Greene, C.H., B.A. Block, D.W. Welch, G. Jackson, and G.L. Lawson. (2009). The emergence of conservation oceanography and its role in the management of marine fisheries. *Oceanography* 22(1): 210-223

Porter, A.D., D.W. Welch, E.R. Rechisky, M.C. Jacobs, P. Winchell, and Y. Muirhead (2009). "Results from the POST Pilot-Stage Acoustic Telemetry Study on Survival of Columbia River Salmon, 2007". Report to the Bonneville Power Administration by Kintama Research Corporation, Contract No. 00040974, Project No. 2003-114-00, 172 electronic pages, (BPA Report Document ID: #P114364), Available at: http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=P114364

Rechisky, E.L., D.W. Welch, A.D. Porter, M.C. Jacobs, and A. Ladouceur (2009). Experimental measurement of hydrosystem-induced mortality in juvenile Snake River spring Chinook salmon using a large-scale acoustic array. *Canadian Journal of Fisheries and Aquatic Sciences*. 66:1019–1024 doi:10.1139/F09-078.

Rechisky, E.L., and D.W. Welch (2010). Surgical implantation of acoustic tags: Influence of tag loss and tag-induced mortality on free-ranging and hatchery-held spring Chinook (*O. tschawytscha*) smolts, in Wolf, K.S., and O'Neal, J.S., eds., PNAMP Special Publication: *Tagging, Telemetry and Marking Measures for Monitoring Fish Populations—A compendium of new and recent science for use in informing technique and decision modalities*: Pacific Northwest Aquatic Monitoring Partnership Special Publication 2010-002, chap. 4, p. 71-96.

Welch, D.W., M.C. Melnychuk, E.L. Rechisky, A.D. Porter, M.J. Jacobs, A. Ladouceur, R.S. McKinley, G.D. Jackson (2009). Freshwater and marine migration and survival of endangered Cultus Lake Sockeye salmon smolts using POST, a large-scale acoustic telemetry array. *Canadian Journal of Fisheries and Aquatic Sciences* 66(5):736-750.

DO MARINE CONDITIONS IN QUEEN CHARLOTTE SOUND LIMIT THE MARINE SURVIVAL OF CHILKO SOCKEYE SALMON?

James R. Irvine[1], Lyse Godbout[1], Leslie Brown[2], Gary Borstad[2], Dave Mackas[1], and Richard Thomson[1]
[1]Fisheries and Oceans Canada [2]ASL Borstad Remote Sensing Inc.

As documented by Grant and Michelsen elsewhere in this report, the marine survival (MS) of Sockeye salmon that returned to Chilko Lake in 2009 was the lowest on record. We have determined that differences between good and poor Chilko MS years coincide with differences in the magnitude of chlorophyll blooms within Queen Charlotte Sound (QCS) in the spring that Chilko Sockeye salmon smolts go to sea. (Chilko Sockeye marine survival is the proportion of smolts that leave Chilko Lake that survive to adulthood.) Chilko Sockeye marine survivals tend to be high when there is a strong chlorophyll bloom in QCS in late March to April, and low when chlorophyll levels are also low (Fig. 1; correlation highly significant with r^2=0.87). There is no relationship between chlorophyll *a* and Sockeye survivals at times other than spring, and the satellite used to generate these chlorophyll estimates was not operating prior to 1998.

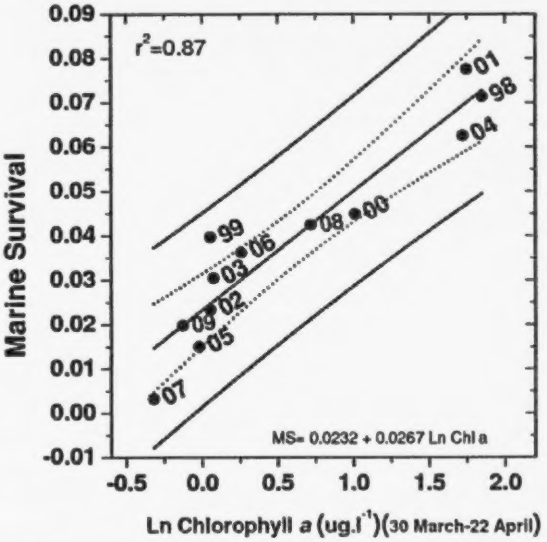


Figure 1. Marine survivals for Chilko Sockeye salmon vs. the natural logarithm of the QCS chlorophyll concentrations (ug.l^{-1}) (black dots) between 30 March and 22 April in the ocean entry year. The central (red) line is the regression line based on data from 1998-2007, adjacent (dotted blue) lines are the upper and lower 95% confidence limits for the regression line, the outer (solid blue) lines are the 95% confidence limits for the data (i.e. 95% of the data are predicted to occur within these lines), and the labels refer to ocean entry years. The Ln chlorophyll a level for 2008 (0.717) and 2009 (-0.128) are also indicated (red dots). The regression equation MS = 0.0232+0.0267 Ln Chl predicts a marine survival of about 4.2% for Chilko Sockeye returning in 2010, with confidence limits of 3.5% and 4.8%, and 2.1% and 6.4%; and about 1.9% in 2011 with confidence limits of 1.1% and 2.8%, and ~0% and 4.2%

Is this high correlation spurious, or does it represent a mechanistic relationship? We cannot say for sure but we hypothesize that intense phytoplankton blooms in QCS during April may result in favourable prey communities being available for young Chilko Lake Sockeye salmon when they migrate through the area about two months later. Earlier or later phytoplankton blooms, as have occurred during most years of low Sockeye marine survival, may result in insufficient or low nutritional value prey for young Sockeye. Assuming that this relationship holds, we project that on the basis of the 30 Mar–22 April 2008 and 2009 Ln chlorophyll a levels in QCS, that the MS for Chilko Sockeye salmon returning in 2010 and 2011 will be around 4.2% and 1.9%, respectively (Fig. 1). This prediction assumes that there is a mechanistic linkage and that ocean conditions in QCS, or perhaps some other area correlated with conditions in QCS, are the primary factor impacting MS.

This work was supported, in part, by funding from the Canadian Space Agency awarded to Richard Thomson and Bill Crawford via the Government Related Initiatives Program.

JUVENILE SALMON SURVEYS IN THE STRAIT OF GEORGIA

R. Sweeting, K. Lange, C. Neville, and R. Beamish, Fisheries and Oceans Canada

The marine survival of **Coho salmon** in the Strait of Georgia continues to be extremely low. We have demonstrated a relationship between the abundance of juvenile Coho salmon in the Strait of Georgia in September (calculated from catch per unit effort (CPUE) in our trawl surveys) and their returning numbers as adults. In 2009, the estimated abundance of Coho salmon in our July and September surveys was below the long-term (1998-2009) average, but an improvement over both 2007 and 2008. Therefore, our forecast for 2010 is for the return to continue to be somewhat below the long-term average (Figure 1). In addition, reports of Coho salmon in the Strait of Georgia during the early part of 2010 (January – March) suggests that this might be an "inside" year for this species and may result in increased sport fishing availability in the strait in the spring and summer of 2010.

The relationship between CPUE of juvenile **Coho salmon** and number that return as adults suggests that the majority of the marine mortality occurs during their first marine summer. Understanding the mechanisms that result in this mortality is critical. Therefore, we continually monitor a number of physical parameters in the strait. Of concern in 2009 was an increase in sea surface temperature (SST). Based on the IOS lighthouse database, the average SST in June-August was, for the first time in the 50 year database, over 18° C. This increase occurred after two years of a decreasing trend, and re-establishes the relatively steady increase in SST over the past four decades. The surface temperature is now at levels that could seriously impact the physiology and metabolism of juvenile salmonids. This temperature is critical as more than 90% of juvenile salmon captured in our surveys are in the top 15 meters of the water column. Temperature stress may contribute to already low marine survivals of Coho and Chinook salmon (Figure 2).

The marine survival of **Chinook salmon** from Strait of Georgia continues to be extremely poor. We have not developed long-term juvenile-adult relationships for Chinook and Chum salmon in our surveys. With Chinook salmon there is the additional complexity of ocean and stream life history types. However, if we use relative changes of Chinook salmon numbers in our catch as an indication of possible returns, the below-average CPUE in the July and September trawl surveys of 2009 would suggests no dramatic improvement in marine survival.

We have poor estimates for total numbers of **Chum salmon** entering the Strait of Georgia each year and do not know the proportion of the population that remains in the Strait of Georgia through to July or September. To reduce the impact of migration on our analysis, we examine the relative change in Chum salmon numbers between survey years for July only. In July 2008 the catches of Chum salmon were less than half of the long term average. If there is a relationship between our survey catch and Chum returns this would suggest poor returns in 2010. In July 2009 the catch of Chum salmon in our survey was the highest observed in the 12 year time series and well over twice the long term average. Thus, while 2010 may be a poor year for the return of Chum salmon, returns in 2011 may be well above average.

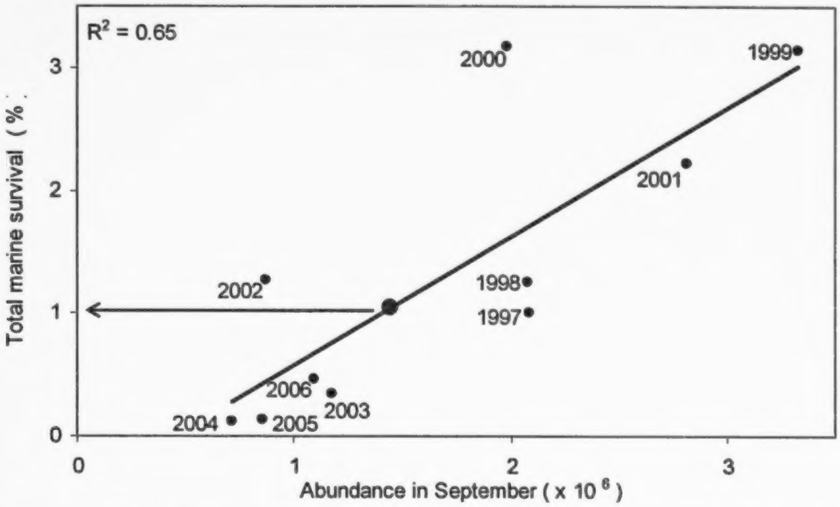


Figure 1. Comparison of ***Coho*** *salmon abundance in September and total marine survival. The prediction of marine survival for Coho that went to sea in 2009 (2010 return) is indicated by red dot. Final survival values for 2007 and 2008 are not yet available.*

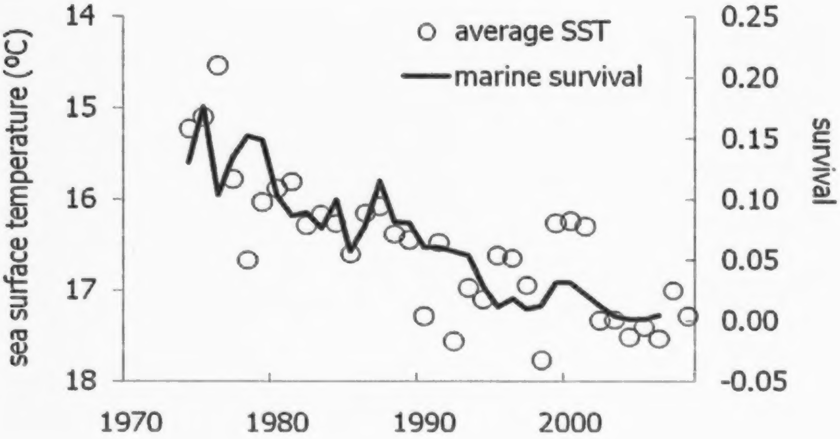


Figure 2. Relationship between SST in the Strait of Georgia and marine survival of ***Coho*** *salmon. The R-squared value for this correlation is 0.52. Note that the temperature scale is inverted.*

CONTAMINANT TRENDS IN THE STRAIT OF GEORGIA

Sophia Johannessen and Rob Macdonald, Fisheries and Oceans Canada

Surrounded by a large and growing urban population, and forming part of a major shipping lane, the Strait of Georgia has received deliberate and accidental discharges of heavy metals, persistent organic pollutants and other contaminants. The history of discharge is reflected in the diverse contaminant profiles measured in sediment cores in the Strait (Figure 1). (This plot shows the historical patterns of discharge, rather than actual concentrations.) Contaminants fall into two categories: "legacy contaminants" whose discharge has ended or been greatly reduced, and "current" contaminants whose use and discharge is ongoing. Once a contaminant has been banned on land, it can continue to cycle through the ocean and marine sediments for decades as a legacy contaminant. Polychlorinated biphenyls (PCBs), for example, were banned in stages commencing in the early 1970s but continue to present a significant threat to marine biota, including killer whales (e.g. Hickie et al., 2007).

The concentration of PCBs in the sediment of the Strait of Georgia is decreasing with time (Figure 2) due to reduced PCB contamination in recent sediments, but active benthic mixing keeps the surface sediment concentration high by recycling deeper, more contaminated sediments. In contrast to PCBs, the concentration of flame retardant polybrominated diphenyl ethers (PBDEs) is increasing rapidly in sediment (Figure 2).

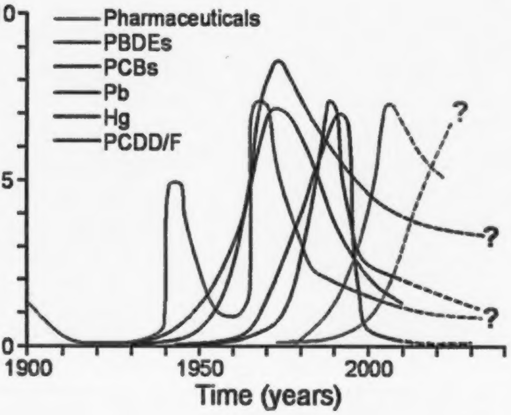


Figure 1. A conceptual presentation of contaminant loading histories to the Strait of Georgia based on sediment core records summarized by Johannessen & Macdonald, (2009). Pb=lead, Hg=mercury; PCDD/F=polychlorinated dibenzo dioxins / furans. The timing on the x-axis is approximately correct, but there are no units on the y-axis, because the fluxes of the various contaminants span several orders of magnitude.

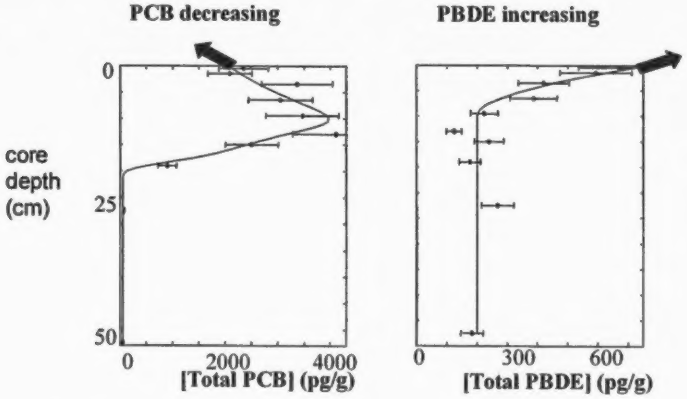


Figure 2. Profiles of PCB and PBDE from a core collected in 170m water depth near Texada Island (Johannessen et al., 2008.) The arrows show anticipated future trends in concentrations over the next decade as sediments accumulate on the ocean bottom.

The production and import of PBDEs have recently been banned in Canada, but they continue to be present in fabrics (curtains, sofas, carpets) and electronics, and emissions from these via wastewater or disposal continue to enter the ocean. PBDEs have already been detected in biota, and we can expect that they will be present for decades, until the discharge ends and natural sedimentation eventually buries them. Pharmaceuticals and personal care products, including artificial fragrances, will require study. Their use is increasing, and many are designed to have biological effects.

Another implication can be drawn from these core records: sediments accumulate with time such that high concentrations associated with earlier, uncontrolled use of contaminants become buried once emissions are curtailed. Surface mixing of the sediments by foraging animals, however, can delay that burial by bringing older material back to the surface. The time taken for surface sediments to lose their contaminant burdens therefore depends on depth of the sediment mixed layer (~10 cm), the effectiveness of mixing, and the rate of sedimentation (usually 0.5-2 cm /yr in sediment accumulation areas of the Strait) and we might expect half-lives of persistent contaminants in surface sediments of the order of a decade (Macdonald et al., 1992). Mercury provides one of the best examples in the Strait of Georgia of how surface mixing and burial control the time taken for sediments to return to background values (Figure 3).

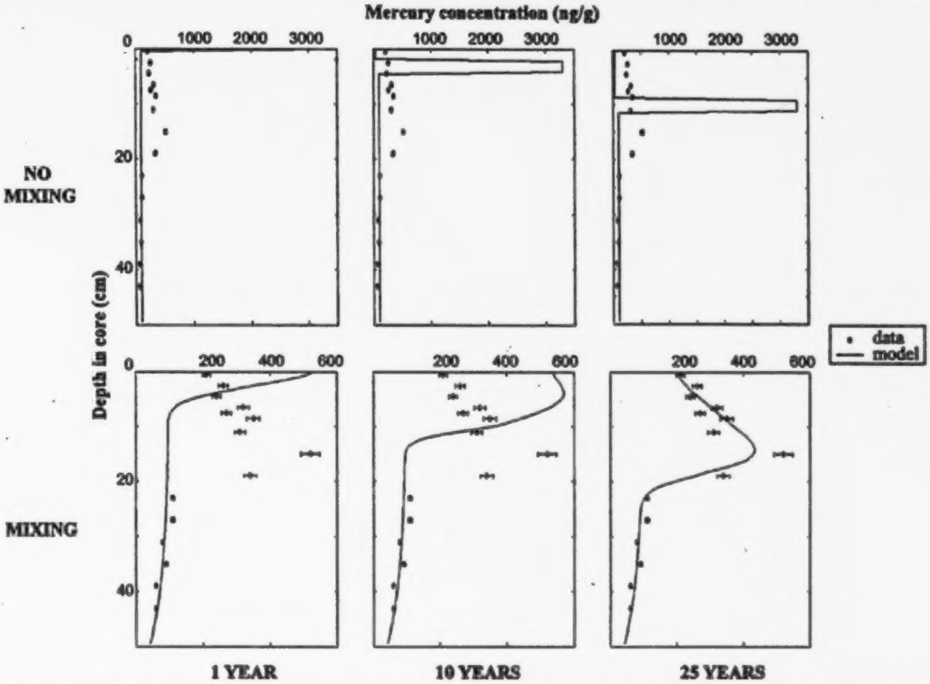


Figure 3. The effect of the mixing model on a hypothetical mercury profile, The source concentration of Hg for all profiles in this figure was a pulse source of 3300 ng/g from 1965 to 1969, 100 ng/g before 1965, and 40 ng/g after 1969. The [Hg] data, mixed layer depth, sedimentation, and (in the lower row) mixing rates are those determined for a core in Howe Sound, an area that received a large discharge of Hg in the late 1960s. The upper row shows the mercury concentration profiles that would have been measured 1, 10, and 25 years after the beginning of the pulse without mixing. The lower row shows the profiles that would have been measured in the same cores with mixing (Johannessen et al., 2005).

References

Hickie, B.E., P.S. Ross, R.W. Macdonald, and J.K.B. Ford, 2007. Killer whales (*Orcinus orca*) face protracted health risks associated with lifetime exposure to PCBs. *Environmental Science and Technology,* 41(18): 6613-6619.

Johannessen, S.C. and R.W. Macdonald, 2009. Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia. *Climate Research*, 40: 1-21.

Johannessen, S.C., R.W. Macdonald, and M. Eek, 2005. Historical trends in mercury sedimentation and mixing in the Strait of Georgia, Canada. *Environmental Science and Technology,* 39(12): 4361-4368.

Johannessen, S.C., R.W. Macdonald, C.A. Wright, B. Burd, D.P. Shaw, and A. van Roodselaar, 2008. Joined by geochemistry, divided by history: PCBs and PBDEs in Strait of Georgia sediments. *Marine Environmental Research*, 66: S112-S120.

Macdonald, R.W., W.J. Cretney, N. Crewe, and D. Paton, 1992. A history of octachlordibenzo-p-dioxin, 2,3,7,8-tetrachlorodibenzofuran, and 3,3',4,4'-tetrachlorobiphenyl contamination in Howe Sound, British Columbia. *Environmental Science and Technology*, 26: 1544-1550.